ECOLOGICAL IMPEDIMENTS TO THE ESTABLISHMENT OF TREES BY DIRECT SEEDING ON PASTORAL SITES IN THE MIDLANDS OF TASMANIA

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Statement of Originality

This thesis contains no material which has been accepted for the award of any other higher degree or graduate diploma in any tertiary institution, and to the best of my knowledge, it contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

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Abstract

Soil degradation resulting from land clearing, tree decline and landuse practices is a serious environmental problem in Australia. While changes in land management practices are required to overcome many degradation problems, and mechanical stabilization techniques will be necessary in many instances, the establishment of trees and other woody vegetation is considered to be an important tool for combating land degradation. Direct seeding is increasingly considered to be a cheap but effective method of re-establishing woody vegetation in rural areas in Australia. It has been used with good results on many rural sites, but in some areas, such as the Tasmanian Midlands, there has been less success.

Broadacre field trials and intensive field and glasshouse experiments were established to investigate direct seeding techniques in the Midlands, and to identify possible factors contributing to results. Results in the field were consistently poor, with low rates of emergence and survival, and very slow growth. In many instances, treatment effects appeared to be masked by harsh environmental conditions. It was demonstrated that germination and survival of three eucalypt species could be significantly increased by irrigation and the resultant increase in available soil moisture. Fertilizer addition, however, was found in glasshouse experiments to depress *Eucalyptus amygdalina* germination.

Pronounced growth check in *E. amygdalina* seedlings grown in both pasture and residual woodland soil in the glasshouse was not overcome by adding moisture. The combination of nutrient addition and weed control did, however, overcome this growth inhibition in pasture soils, as did heat sterilization at 70°C. From this result it was hypothesized that growth check in *E. amygdalina* seedlings grown in pasture soil was a result of a soil nutrient imbalance and/or an unfavourable soil microflora.

Competition studies revealed that both a grass, *Lolium perenne*, and a broadleaf, *Leontodon taraxacoides*, significantly decreased the seedling growth of one eucalypt species. The importance of long term weed control in promoting growth was clearly demonstrated both in the field and glasshouse. It was found that long term weed control could be improved by soil scalping or the use of residual herbicides.

E. amygdalina growth was stimulated by competition from acacia seedlings, which may have been a result of increased nitrogen nutrition as a consequence of the nitrogen fixing capacity of acacias, or of a more favourable environment for the development of appropriate soil microflora resulting from an increase in root density.

Experimental results suggest that eucalypt seedling emergence, survival and growth may be enhanced by site preparation techniques which modify the microenvironment to increase soil moisture levels and provide protection from extreme temperatures; by good long term weed control; by the the post-emergence addition of fertilizer; and by sowing high rates of acacias in combination with eucalypts. Results may also be improved by sowing at a time of year when soil moisture conditions are more favourable, or when the activity of seed harvesting organisms is low. Until there is a greater understanding of the processes causing growth inhibition in eucalypt seedlings in the Midlands, however, direct seeding may not be an appropriate technique on many long term exotic pasture sites, or in some remnant stands of native vegetation.

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Preface

The work outlined in this thesis began with a research project funded by the National Soil Conservation Program and the Forestry Commission, Tasmania, in which tree establishment techniques suitable for the Tasmanian Midlands were investigated. As part of the work, direct seeding techniques successfully used on mainland Australia were investigated in the field, to determine whether direct seeding would be a cheap and effective means of woody vegetation establishment in the Midlands. Establishing trees by direct seeding, however, proved to be more difficult than was originally envisaged, with environmental conditions exerting a significant effect on results and apparently masking treatment effects. I realized that more intensive experimental work, in which some environmental variables could be controlled, would be necessary to develop an understanding of why direct seeding was unsuccessful, and to hopefully overcome these problems. Hence, the second part of the project was initiated. This second stage was originally field-based, consisting of an experiment in which soil moisture content was manipulated for a range of treatments. The results of this experiment were, however, inconclusive, and glasshouse trials were therefore established to explore the processes influencing results in the field.

The combination of field and glasshouse experiments has allowed me to identify some of the ecological impediments to the establishment of trees by direct seeding at one site in the Midlands, but it has become clear that much more research will be required before this complex problem is fully understood.

CHAPTER 1. General Introduction

Introduction

Almost two thirds of Australia's forests and one third of all scrub and woodland has been cleared in the 200 years since European settlement (Campbell 1991). As well, because natural regeneration processes have in many areas been impeded or interrupted by land management practices, there is a progressively aging population of remnant vegetation and a resultant attrition due to death by old age. In addition, large areas of remnant vegetation are dying due to a phenomenon known as rural dieback, most dramatically illustrated in the New England area of New South Wales (White 1987), but also found in many other rural areas, including the Midlands of Tasmania. Rural dieback is the premature and relatively rapid decline and death of vegetation due to the interaction of stresses related to agricultural enterprises, clearing, old age and drought (McMurray 1988).

As a result of this loss of native vegetation, and of land management practices, land degradation is now a major environmental problem in rural Australia. Loss of woody vegetation changes the balance between rainfall, evapotranspiration, infiltration and runoff (Clarke 1986), thereby increasing the incidence of erosion, landslips, soil slumping and rising water tables. In consequence, there may be an increased incidence of flooding, siltation, waterlogging and soil salinity (Temple-Smith 1988). Such problems have often been exacerbated by soil cultivation (Clarke 1986), which has also resulted in soil compaction in some areas, and has led to the spread of exotic pathogenic organisms in many soil types. The widespread use of chemical fertilizers associated with agriculture has resulted in soil acidification is some areas (McGarity and Storrier 1986). Land clearing and agricultural practices expose the soil to greater temperature extremes and increased desiccation, which may alter biological activity and result in reduced concentrations of nitrogen and organic carbon (Burch 1986). Both have led to the extinction of native plant species and a simplification of plant communities.

The estimated cost of repairing agricultural land suffering degradation, and the possible economic losses due to that degradation, are enormous, with more than half of all rural land believed to require some form of restorative action (Campbell 1991). Burch (1986) and Clarke (1986) consider that changes in land use practices will be important if land degradation is to be overcome. The establishment of woody vegetation in appropriate locations can also be used to stabilize degraded sites and to regulate the water table (Oates 1983; Temple-Smith 1988). Plantations of woody vegetation on farms have the added advantage of increasing ecological diversity and providing shelter for stock and crops, both of which can lead to substantial gains in farm productivity (Ferguson 1984; Tisdell

1984). In recent years, interest in re-establishing woody vegetation on farms has increased dramatically, as has knowledge of land degradation problems in agricultural areas. This is perhaps best illustrated by the proliferation of landcare and farm tree groups throughout Australia. The scale of revegetation required to redress land degradation in Australia is, however, large, and it is necessary to develop establishment techniques which are cheap but effective, applicable to a wide range of sites, and which provide a psychological incentive to undertake the work (ie are successful).

There are three main techniques used for native tree and shrub establishment. Hand planting of nursery-raised seedlings is generally considered to be the most reliable technique. Good site preparation and plantation maintenance can result in the survival of 75 to 100% of seedlings. As they are planted with a developed root system, such seedlings are more resilient to climatic fluctuations, and can quickly establish and grow when conditions are favourable. However, the planting process is time consuming, and expensive, particularly in harsh environments where irrigation and individual shelters may be necessary to achieve the desired stocking rate. In Tasmania, the estimated cost of establishing a hand-planted seedling ranges from $5.00 (J. Waugh, Greening Australia, pers. comm.), to $12.00 (G. Clarke, Forestry Commission, Tasmania, pers. comm.), depending on the techniques used. This renders hand planting an unsuitable method for broadacre revegetation, although it may be the most appropriate method at some sites.

Residual woodland management, while perhaps the cheapest option in some instances, relies on the existence of healthy remnant vegetation to provide a seed source for regeneration. This method, which involves fencing remnant vegetation and, sometimes, applying an appropriate grazing regime, has a significant role to play in localized genepool conservation, but in many parts of Australia remnant vegetation has not survived. Thus the method has a limited, but undeniably important, role to play in rural revegetation.

A method which is currently receiving much attention in Australia is direct seeding. It is potentially cheaper than hand planting, and may be useful for broadscale revegetation on a wide range of sites. Direct seeding is increasingly touted as the revegetationist's panacea, but although it has been used successfully for many years in the non-rural sector and has proved useful for farm tree establishment on some sites, it is a relatively untried approach to rural revegetation in many parts of Australia.

What is direct seeding?

Direct seeding is a technique of establishing vegetation which involves sowing seed directly into the ground to be revegetated. It is a method long-used in the establishment of agricultural crops, but has generally played a minor role in the development of plantations of woody species such as trees and shrubs. Interest in direct seeding of tree and shrub species is due mainly to a number of perceived advantages:

* if successful, direct seeding is a relatively fast method of establishing woody vegetation, because the process can be mechanized and large areas can be sown in a day;
* the potential cost of establishing plantations using direct seeding is much lower than the cost of conventional plantation establishment techniques;
* seedlings developing from direct sown seed are less likely to develop the deformed root systems that are sometimes a problem with transplanted seedlings;
* the shock and possible temporary growth check related to transplanting may be avoided;
* natural selection processes can operate to a greater degree on direct sown seedlings than in a nursery situation, favouring seedlings best suited to a particular site or range of conditions;
* direct sown seedlings seem less prone to browsing damage, and such plantations often look more natural than do those established with hand planted seedlings.

As well as advantages, there are also a number of possible disadvantages associated with direct seeding:

* failure of direct sown plantations is more common than is failure when using nursery raised seedlings, as both seed and newly-emerged seedlings are vulnerable to environmental extremes;
* whereas tubestock can be planted at almost any time of the year provided there is sufficient soil moisture, successful direct seeding is reliant on particular climatic/seasonal conditions being met to stimulate germination and growth;
* good quality seed may not be readily available and may therefore be expensive;
* once the seed has been sown, it is vulnerable to insect predation, fungal attack and strengthening of dormancy (Grose 1963; Copley and Venning 1983; Clemens 1984);
* in dry environments, germination, survival and growth are often poor, and seedlings can have up to a two year growth disadvantage compared to nursery-raised seedlings (Rindt *et al.* 1953).

Factors influencing direct seeding

Whether direct seeding is successful or not may rely on a number of factors, which can influence seedling emergence, survival and growth. The most important are considered by many authors to be weed competition, moisture availability, weather conditions and seed harvesting activities.

Weed competition

A species' ability to emerge, survive and grow in a particular environment is partly related to its competitive interactions with other species (Harper 1977; Goldburg and Fleetwood 1987; Miller and Werner 1987). Competition is defined in this instance as any direct or indirect negative effect of one plant on another, and includes competition for resources and effects such as allelopathy (Harper 1977; Fowler 1986). To be successful in competition, a species must have either a low response to the abundance of other species, and/or such a large effect that the abundance of the other species is greatly reduced (Miller and Werner 1987). There has been considerable research into the effects of weed competition on the growth of tree species commonly used in forest plantations. In such cases, competition may be caused by trees, grass, bracken, and assorted other woody species. Jack (1970) found that up to 2 years growth of *Pinus radiata* (D. Don.) was lost during establishment due to competition from dense herbaceous weeds. Nazer and Clark (1984) suggested that control of both broadleaf and grass species was important if tree growth was to be improved by weed control, although Gordon *et al.* (1989) found that grass had a greater competitive effect against *Quercus douglasii* (Hook & Arn.) than did the broadleaf species *Erodium botrys* (Cav.). Severe moisture stress, induced by weed competition, was found by Sands and Nambiar (1984) to be a major factor inhibiting the growth of *P. radiata*, whereas competition for nutrients by a grass species was found by Ellis *et al.* (1985) to greatly decrease the growth of *Eucalyptus delegatensis* (R.T. Baker.) seedlings.

Moisture availability

The level of moisture available at the time of germination is generally regarded as critical for the germination process to occur and for the survival and growth of newly-emerged seedlings (eg Zohar *et al.* 1975; Edgar 1977; Bachelard 1985). Without an adequate supply of moisture, both rate (speed) and percentage germination can be substantially decreased. Cunningham (1960) suggested that *Eucalyptus regnans* (F. Muell.) seed required a moisture content of 50% for germination to occur, and Gibson and Bachelard (1986) found that *Eucalyptus sieberi* (L. Johnson.) seed required a least a 30% moisture content, maintained for approximately 60 hours, before germination processes would commence. Periods of wetting and drying may influence a seed's capacity to germinate.

Gibson and Bachelard (1986) reported that up to four wetting and drying cycles increased the rate of *E. sieberi* germination, but did not affect germination percent. However, more than four cycles progressively reduced a seed's capacity to germinate normally.

Moist soil may, relative to dry soil, reduce soil temperatures by as much as 10°C (Cunningham 1960; Roberts 1972), which may decrease the incidence of heat-induced secondary dormancy and of seedling tissue damage due to high temperature stress. This may significantly increase establishment in some instances.

Tree seedling growth has often been found to increase with greater available soil moisture. Nambiar and Zed (1980) and Sands and Nambiar (1984) reported greater growth and reduced mortality in *P. radiata* when moisture stress was decreased by weed control. Cromer (1980) found that irrigating *P. radiata* substantially increased seedling height and diameter.

Temperature

Temperature extremes have been found by a number of authors to affect seedling establishment (Cunningham 1960; Cremer 1962; Nobel 1984; Childs and Flint 1987; Flint and Childs 1987). High temperatures can induce secondary dormancy in seed, and may kill seed embryos if imbibition has commenced (Roberts 1972). At low temperatures, the capacity of seed to germinate may be greatly reduced, resulting in lower rate and percentage germination (Grose 1963; Roberts 1972; McLeod 1981). However in some instances low temperatures may assist in fulfilling the cool moist stratification requirements necessary in some species before germination will commence.

Both high and low temperatures can cause plant tissue damage. High temperatures are generally only fatal to cotyledonous seedlings (Cunningham 1960), and the impact of such temperatures on seedlings often decreases with increasing plant size (Nobel 1984). Such damage can, however, result in the loss of substantial numbers of seedlings (Cunningham 1960). Low temperatures, as well as causing tissue damage, can result in frost heave, which often uproots small seedlings and leaves them vulnerable to desiccation. Cremer (1962) considered frost heave to have a more significant effect on seedlings than tissue damage due to frosting.

Weather conditions

Weather conditions may significantly affect germination, survival and growth. Greater exposure to solar radiation may induce localized drought, and seasonal variation in soil moisture levels may result in desiccation of emergent seedlings. Wind can increase soil drying and evaporation from plant material, resulting in water stress. In addition, when soils are sandy, sand-laden wind can cause tissue damage.

Seed predation

Ants, rodents and insects have all been implicated in seed harvesting activities in various parts of the world and for a range of plant species (Cremer 1965; Cremer 1966; Russell *et al.* 1967; Johns and Greenup 1976; Purdie 1977; Ashton 1979; Drake 1981; Buckley 1982; Andersen and Ashton 1985). For many species of Australian plants, dispersal and survival of seeds is intimately associated with harvester communities (Majer 1990). Although a large proportion of seed may be lost in this way, harvesting organisms may move seed to favourable germination sites, and many plant species have developed adaptations to encourage some degree of harvesting.

Cremer (1966) found that a large proportion of *E. regnans* seed sown in the Florentine Valley in Tasmania was destroyed by the lygaeid beetle *Euander lacerosa* (Erichson.). Buckley (1982) refers to rodents in northern America consuming large quantities of sown seed. Ant predation of fallen seed was frequently observed on burnt sites by Purdie (1977), and Pryor and Clarke (1964) experienced problems with seed harvesting ants when eucalypt seed was direct sown onto pasture sites. It is probable that many species of plants used in minesite rehabilitation in Australia are affected by seed harvesting activities (Majer 1990), and Majer (1990) hypothesizes that there is likely to be a similar problem on many direct sown farmland sites.

Techniques for enhancing establishment

In many parts of Australia, problems with direct seeding have been overcome, and vegetation has been successfully established in this way. A number of processes are generally recommended to improve establishment results.

Soil preparation

Soil preparation prior to plantation establishment is considered by many authors to be important for successful seedling establishment, although most work has been done with nursery-raised rather than direct sown seedlings (McKimm and Flinn 1979; Cullen and Mason 1981; Runciman and Malcolm 1985; Oates and Clarke 1987; Odermatt 1990; Foster and Dahl 1990). McKimm and Flinn (1979), Walker (1979) and Cullen and Mason (1981) reported greater survival and more vigorous growth in seedlings growing in cultivated and, particularly, deep-ripped soil. Sharp (1985), however, measured no definite response to deep ripping from direct sown seedlings, and Burns (1987) found that while deep ripping increased germination, there was no effect on survival. Geard

(1986) and Bird *et al.* (1990) found that mouldboard ploughing gave good results, and Bird *et al.* (1990) measured increased germination and survival following direct seeding onto soil that was both ripped and scalped.

Soil preparation can be important for a number of reasons. Sheldon (1974), Harper (1977) and Fowler (1988) discuss the importance of microsite variation in enhancing seedling establishment. Increased microsite variation results in a greater number of microniches offering favourable moisture conditions and protection from harsh environmental conditions, browsing and competition from other individuals. Soil preparation can increase microsite variation.

Compaction problems can also be overcome by soil preparation. A number of authors have suggested that compacted surfaces, while not necessarily affecting germination, may severely limit seedling establishment (Evans and Young 1972; Sheldon 1974; Harper 1977). Soil compaction can also hinder gas exchange and water and nutrient flow in the soil (Lindberg and Petersson 1985).

Surface crusts form on many soil types, from the impact of raindrops and sunshine (Lemos and Lutz 1957; Sheldon 1974), and can severely impede seedling establishment. While soil cultivation will break up existing soil crusts, cementation may again occur following subsequent rain. Surface crust formation following direct seeding may prevent or greatly reduce seedling establishment (Sheldon 1974; Harper 1977). Soil preparation which increases microsite heterogeneity may increase the number of microniches in which secondary crust formation is delayed, which may have a significant effect on overall establishment.

A number of other reasons are cited in favour of soil preparation prior to direct seeding. Walker (1979) suggests that deep ripping increases soil water penetration, and it may allow better vertical root growth (Cullen and Mason 1981). On frosty sites, Cullen and Mason (1981) found that discing greatly improved seedling survival and gave moderate increases in initial growth. Soil scalping has been found to give good long term weed control (Venning 1985; Marriot 1987). Soil preparation which increases microsite variability may reduce seed harvesting (Majer 1990).

In addition to soil preparation, other methods of providing protected regeneration niches have been investigated. Geard (1986) reported better establishment in the Midlands of Tasmania when shelter, in the form of bottomless plastic cups, was provided to seedlings. Other authors consider that adequate protection can be given to emerging seedlings by the cheaper option of sowing a cover crop, which is usually a fast-establishing grass species, sown at a low rate per hectare in conjunction with woody species (Clemens 1984). The grass is sown to provide protection to the slower-growing native species. Clemens (1984), however, considers that, as grass species generally establish more rapidly than tree and shrub species, there is a danger that cover crops will compete vigorously and to the detriment of sown woody species. Indeed, Burns (1987) found that a cover crop sown at a high density decreased seedling height after 12 months, although survival was increased. He recorded reduced wind exposure and higher gravimetric soil moisture levels around seedlings grown at high rather than at low cover crop densities.

Mulching may also increase microsite variability. As well, mulch has been reported to decrease soil temperatures (Flint and Childs 1987), although the incidence of frosts at some sites may be increased by the presence of mulch material (Hall 1985). A range of mulch materials have been successfully used in direct seeding operations, such as slash (Duckett 1987; Hinz 1990), bitumen spray (Dalton 1990), sand, vermiculite (Runciman and Malcolm 1985), black plastic and cardboard (Flint and Childs 1987).

Weed control

Weed control can be achieved by both chemical and mechanical means. Mechanical methods were found by McMurray (1985a) and Revell (1976) to give shorter periods of suppression than the use of chemicals, although soil scalping may result in long weed free periods (Marriot 1987). Due to the possibility of root damage, mechanical methods are probably inappropriate for post-emergence weed control (Nazer and Clark 1984).

Chemical weed control can be undertaken using either foliar-applied knockdown herbicides, residual herbicides, or a combination of the two. Both broad spectrum and selective herbicides are available under each of these categories. Knockdown herbicides act on existing root and shoot material, whereas residual herbicides are absorbed by both established and emerging plants. They remain active in the soil for a period of time following application, thereby providing a longer period of weed control than knockdown herbicides. For this reason, residual herbicides are favoured by many authors for pre-sowing weed control (Venning 1988; Dalton 1990; Bird *et al.* 1990). It is often recommended, however, that when residual herbicides are used in conjunction with direct seeding, the soil in the vicinity of sown seed is either left unsprayed, or is scalped or cultivated prior to sowing, to minimize the chance of contact between active herbicide and sown seed (McMurray 1985a; Venning 1988).

Fertilizer addition

Many authors have reported significant growth responses in tree seedlings to added fertilizer. Ward *et al.* (1985) and Schonau and Herbert (1989) both detail increased height and diameter in a range of eucalypt species in response to added fertilizer, although the degree of response appears to vary with site, species and type of nutrient applied. Fertilizer addition has been shown to increase root as well as shoot growth, and for this reason Lahiri (1980) suggests that fertilizer addition in times of periodic drought may increase seedling survival and growth.

There is less agreement on the effects of fertilizer addition on seedling emergence. Weatherly (1985) found no detrimental effects on the germination of a range of native species coated in nutrient powder. Lockett (1978), however, measured reduced emergence and survival of *Eucalyptus obliqua* (L'Herit.) seedlings grown in glasshouse experiments with three different fertilizer types. The Victorian Department of Conservation, Forests and Lands (Anonymous 1986) warns that storing eucalypt seed and fertilizer together for any period of time may reduce seed viability.

Sowing rate

The volume of seed sown onto a site can be expected to influence the number of emergent seedlings, although results will be influenced by both seed viability and site characteristics (Oates and Clarke 1987; Campbell *et al.* 1988; Venning 1988). As an example, *E. delegatensis* seed viability varies between approximately 30 000 and 200 000 seeds kg^{-1}, with a mean of approximately 100 000 seeds kg^{-1}. In the field, environmental and site factors can result in a percentage emergence ranging from less than 200 emergents kg^{-1} of sown seed, to in excess of 50 000 kg^{-1} (Battaglia 1990a), which will obviously be reflected in the number of established seedlings.

It is generally recognized that a large number of eucalypt germinants fail to survive. Campbell *et al.* (1988) consider 7% to be the highest percentage survival which can be expected on farmland, whereas Venning (1988) suggests 1% for small-seeded and 5% for large-seeded species. This may, however, be too general for some sites, particularly where conditions are harsh.

Seed Pretreatment

The germination of some plant species can be enhanced by pretreatment prior to sowing, to remove either physical or physiological dormancy (Grose 1963; Turnbull and Doran 1987; Venning 1988). For example, the hard seed coat of many leguminous plants prevents moisture penetrating to the seed embryo, thus preventing germination. This can be overcome by a number of techniques, such as heat treatment with boiling water, scarification of the seedcoat, or treatment with acid (Clemens 1984; Turnbull and Doran 1987; Venning 1988), although the most appropriate method is likely to vary with species (Clemens 1984; Turnbull and Doran 1987).

Some species have a requirement for cool moist stratification before germination will occur (Grose 1963). Unless the seed of such species is stratified prior to sowing, germination may be spread over a number of seasons, with consequent loss of seedbed, and loss of seed to predators and pathogens. Venning (1988) notes that techniques such as scarification and soaking seed in a 1% solution of potassium nitrate for 48 hours an also overcome dormancy in eucalypts. Boden (1957) reported the breaking of dormancy in some eucalypt species when seed was soaked in cold water for 48 hours. Grose (1963) suggests that dormancy requirements in eucalypt species can be met by direct seeding in autumn, and allowing cool moist stratification to occur naturally. This process, however, risks loss of seed to fungal and insect attack.

Turnbull and Doran (1987) list the pretreatment requirements of a number of Australian native plant species.

Time of sowing

Time of sowing can influence both rate (speed) and percentage germination, and survival. Germination is influenced by environmental factors such as moisture availability, temperature and light, and biotic factors such as the presence or absence of soil pathogens (Roberts 1972; Hartman and Kester 1975), all of which may vary seasonally. While, generally, unimbibed seed can withstand a range of temperatures without adverse effects, secondary dormancy may be induced in some species at some temperatures (Grose 1963). Germination of imbibed seed will only occur within a limited temperature range, with supra- or sub-optimal temperatures either killing seed or inducing dormancy. Generally, some germination will occur between the temperatures of 11°C and 37°C (Grose 1963; McLeod 1981). Thus temperatures at the time of sowing may significantly influence the results achieved.

Time of sowing may be influenced by the degree of weed control achievable in a given season. Many authors suggest that weed control can be more effective in spring than autumn in southern Australia, and on this basis recommend spring sowings (Geard 1987; Oates and Clarke 1987; Bird *et al.* 1990). The rate of seed removal by harvesting organisms can vary with season, and, at sites where seed predation can be expected to be high, this factor may be important in determining the appropriate sowing time (Andersen 1983; Andersen and Ashton 1985; Majer 1990). In addition, the anticipated size of seedlings at the onset of unfavourable seasonal climatic conditions, such as high or low temperatures or drought, should be considered when appropriate times of sowing are being investigated.

Direct seeding in Australia

The process of establishing woody species by direct seeding is not new, being most commonly associated with silvicultural practices in higher rainfall areas. Direct seeding has been used for more than two centuries to revegetate forests in many European countries (Rindt *et al.* 1953), and is an important method of establishing conifers in the United States and Canada (Schubert *et al.* 1971; Hellum 1973). It is also used in some forest types in countries such as Chile and Britain (Gerandog 1981).

In Australia, direct seeding has been used for decades to revegetate logged coupes in southern eucalypt forests. In the mining sector, the techniques have been used for revegetating mine sites for over 20 years. On agricultural lands, direct seeding of tree species was recorded in Victoria as early as 1876 (Sharp 1990), and was used at the beginning of this century to establish plantations of acacias in Victoria and South Australia for tannin production, and eucalypts for windbreaks (Venning 1985). One 'recipe' which apparently gave successful results in Victoria was to sow on each acre of worked ground,

> *"half a pound (of seed) for the trees, half a pound for the ants, and half a pound for luck"* (Youl 1986).

Many of these early-established plantations are still in existence, managed for shelter and timber.

More recently, the extensive use of chemical fertilizers and the introduction of improved pasture species has reduced the success of direct seeding in agricultural areas throughout Australia (Venning 1988). Experiments in New South Wales in the 1960's indicated that direct seeding into a pasture environment gave extremely variable results due to variability in site and season, and it was concluded that an investigation of planting techniques was more appropriate for such sites (Pryor and Clarke 1964). Since that time, there has been considerable research in some states into appropriate direct seeding techniques for use in the rural, urban, mining and forestry sectors. Following is a brief and general description of techniques used throughout Australia.

Forestry

Direct seeding is a major regeneration technique used in Tasmanian and Victorian eucalypt forests following logging. In both states, a competition-free receptive seedbed is considered essential, produced either by burning following logging, or mechanical disturbance. Sowing closely follows seedbed preparation, and is timed to coincide with conditions favourable to germination, namely autumn or occasionally early spring

(Lockett 1991). The most common method of sowing is by aerial application, but hand broadcasting or spot sowing is used on small sites and for infilling. Sowing rates average 0.5 - 0.7 kg ha^{-1} in Tasmania, although this is higher if regeneration problems are expected or if seed viability is low. In Victoria, seed is pelleted with kaolin and insecticide (Manderson 1985), as insect seed harvesting is considered to be a major problem. The kaolin is also believed to ensure an even flow of seed during sowing. In Tasmania, experiments have suggested that seed coating offers no advantages.

A small amount of direct seeding is conducted in New South Wales, although the major emphasis appears to be on natural regeneration, lignotuberous regeneration and plantation establishment techniques (Anonymous 1982). Similar methods are used to those implemented in Tasmania and Victoria.

Mining

Much developmental work has been conducted by mining companies over recent years, in an attempt to formulate cheap and effective methods of establishing vegetation on disturbed sites, many of which offer major impediments such as inappropriate drainage, lack of topsoil, soil acidity, and the presence of heavy metals. Direct seeding has been investigated in a number of cases, often giving results superior to those obtained using other revegetation methods (Hinz 1990).

In all states, site modification is considered essential for effective minesite rehabilitation. Deep ripping, soil scarification, and techniques for water harvesting and soil stabilization are all mentioned. In the Northern Territory, Hinz (1990) recommends use of slash material spread over a sown site to provide both soil stability and protection from desiccation. Duckett (1987) has also used slash material in wetter areas of Tasmania, for protection from frost and browsing. Cover crops of species such as ryecorn and millet have been used in Tasmania and New South Wales (Duckett 1987; Burns 1987).

The application of fertilizer to the sowing mix is recommended in some states. In Tasmania, fertilizer is added to nutrient-deficient sites (J. O'Donnell, Hydro Electric Commission, pers. comm.). In Queensland, seed is mixed with fertilizer prior to sowing (Foster and Dahl 1990). Burns (1987) investigated a range of fertilizer rates and nutrient combinations for use in mine rehabilitation work in New South Wales, with favourable results, and in Western Australia, Brooks and Jeffries (1990) recommend the use of fertilizers on some sites.

Sowing is timed in the Northern Territory and Queensland to coincide with the onset of the monsoon. In wetter parts of Tasmania and in Western Australia, the recommended sowing time appears to be autumn and winter.

Urban/aesthetic

On a more limited scale, direct seeding has been used in urban areas and for the establishment of roadside vegetation. Burke *et al.* (1990) investigated direct seeding techniques suitable for use in Melbourne.

The techniques have also been applied in the rehabilitation of erosion-prone areas near Perth, and in the establishment of roadside vegetation in Western Australia (Loney 1990), Victoria (BWD), and Tasmania (J. Gillian, Department of Roads and Transport, pers. comm.).

Agricultural

In the rural context, direct seeding has been well developed in Victoria, Western Australia and South Australia, and used to a limited extent in most other states. Often the successful techniques are the same in each state, incorporating some form of site modification, adequate long term weed control, an appropriately-defined sowing time, and the use of viable seed. The techniques investigated include hand broadcasting; the use of specialized seed drills; soil compaction after sowing; the use of mulches; fertilizer addition; cultivation techniques such as discing, mouldboard ploughing, burning and soil scalping; and the use of a range of herbicides. Seed pelleting has been investigated to a limited extent (Weatherly 1985; Marriot 1987), although the results from trials using unpelleted seed appear to suggest there is no real advantage from pelleting (Venning 1988).

Most authors in Victoria recommend spring rather than autumn sowings in southern parts of the state (eg Sharp 1985; Weatherly 1985; Oates and Clarke 1987), as better weed control is achieved at this time. In drier areas, winter sowing is recommended (Campbell *et al.* 1988). In South Australia, sowing in early winter is advocated for drier areas (300 - 400 mm rainfall), and early spring is recommended for areas with rainfalls in excess of 700 mm (Dalton 1990). Preliminary results in Tasmania suggest that early spring sowings may give better results than autumn sowings (Geard 1986).

In Western Australia and in more arid areas of South Australia, physical soil treatments such as soil pitting, furrowing, deep ripping and topsoil grafting are advocated (Malcolm and Allen 1981; Loney 1990; Malcolm 1990; Odermatt 1990; Walker 1990). Such treatments can assist water infiltration, channel water to seed or seedlings, and protect seedlings from strong winds.

Sowing rates recommended for direct seeding in rural areas appear to fall within the range of 1 - 3 kg ha^{-1}. Many authors stress the importance of considering seed viability when choosing a sowing rate (Anonymous 1986; Marriot 1987; Venning 1988).

Direct seeding in rural Tasmania

In Tasmania, direct seeding has only been investigated to a limited extent. Very few landholders have tried direct seeding, possibly due to lack of knowledge of suitable direct seeding and seed collection techniques. While methods similar to those used successfully in other states have been investigated, the results have been far from satisfactory in most cases.

Early trials in Tasmania were established to investigate the use of direct seeding in revegetating land in the Midlands of the state, an area suffering from severe tree decline and other land degradation problems (see Appendix 1). Work concentrated initially on conventional forestry regeneration techniques, and later broadened to include a number of the techniques considered successful in other states. From these trials, three major conclusions were reached. Firstly, direct seeding was not going to provide an easy solution to revegetation problems in the Midlands. Secondly, the results from direct seeding were likely to be highly variable even if suitable techniques could be developed, due to the variable environment of the Midlands. Finally, before direct seeding would be successful, more investigation of the environmental impediments was required.

As well, a number of specific observations were made:

* spring sowings appeared to be superior to autumn sowings, due to the unreliability of the autumn break in weather in the Midlands, and because better weed control could be achieved in spring;
* shelter, in the form of bottomless plastic cups, increased seedling germination and survival;
* competition from pasture species appeared to be a major inhibiting factor in the establishment of trees by direct seeding;
* soil cultivation without herbicide application tended to increase the density of weeds;
* weed species quickly re-established following the use of knockdown herbicides, and the use of residual herbicides appeared to suppress eucalypt germination;
* better results were achieved if the seed was slightly buried;
* sowing was not successful on long term pasture sites, lighter soil types or on elevated sites, but was quite successful on sites newly cleared of vegetation. (Geard 1986; 1987).

Scope of this project

The following work was initiated to investigate more closely the usefulness of direct seeding for tree and shrub establishment in the Midlands. Early research entailed broadacre field trials, in which techniques used successfully in similar environments in other parts of Australia were investigated. The aim of this work was to determine whether direct seeding was a cheap and effective method of tree establishment in the Midlands. The results of these experiments are outlined in Section A.

In Section B, a number of detailed field and glasshouse experiments are described, which were established with the aim of identifying the causes of the establishment problems identified in Section A, and methods of overcoming these problems.

Section A

BROADACRE FIELDWORK

CHAPTER 2. Preliminary Field Trials

Introduction

Problems associated with the establishment of vegetation in the Midlands by direct seeding were illustrated in early work by Geard (1986; 1987), who measured poor germination, growth and survival of species at a number of sites over a range of seasons and years. This he attributed to poor long term weed control, and to adverse environmental conditions. However, Geard's work was preliminary and had a number of limitations. Seed viability and emergence were not compared, and only a limited number of techniques were studied.

The following experiments aimed to investigate, on a range of sites in the Midlands, some of the establishment prescriptions used successfully in similar environments on the mainland. They consisted of experiments investigating weed control and soil preparation techniques, sowing rates, sowing times, and the effect of cover crops on establishment. There was no replication in time in any experiment,which is overcome to some extent by comparing the climatic data collected during each experiment with the average data from nearby Australian Bureau of Meteorology monitoring stations.

These trials are, as the chapter heading suggests, only preliminary field experiments. They have been included to provide a background to the experimental work in Section B and should be considered in this context.

Experiment 1. The effect of weed control regimes and sowing rates on direct seeding in the Midlands

Methods

In 1988, experimental sites were selected on the properties 'Wetheron' (Site 6), 'Grove House' (Site 4) and 'Fosterville' (Site 5) (site numbers correspond to those in Appendix 1). At each site, a split plot 4 x 2 factorial design in randomised blocks was established, with four herbicide treatments and two sowing rates. Herbicide treatments were applied at the plot level, and sowing rates at the sub-plot level. Site 6 was replicated twice in blocks of 20 x 60 metres; Site 4 was replicated three times in blocks of 20 x 60 metres; and Site 5 was replicated three times in blocks of 20 x 40 metres. All sites were fenced from domestic stock.

Herbicide was applied in July. The four treatments entailed either strip or blanket (total plot) application of glyphosate, a knockdown herbicide, or a mixture of atrazine (a residual herbicide) and glyphosate. Glyphosate was applied at a rate of 5 litres ha^{-1} and a ratio of 50:1 water to herbicide. Atrazine was applied at 6 litres ha^{-1}. In plots where both glyphosate and atrazine were applied, they were sprayed separately to avoid denaturation of the glyphosate in the clay-based atrazine. Where herbicide was applied in strips, the sprayed lines were spaced at 0.5 metre intervals. In all plots excellent sward control was achieved, and at the time of sowing in September, there was close to 100% weed control.

The control treatment was considered to be blanket application of glyphosate, and a sowing rate of 100g km^{-1}.

Sowing was done with a Western Tree Seeder (Figure 2.1), which is a machine designed specifically for sowing tree and shrub seed in farmland situations. It has a single opening tyne, followed by two offset cultivation discs, a drop tube down which seed is fed from a seed box onto the cultivated soil, and a press wheel which enhances soil-seed contact. The species included in the sowing mix are listed in Table 2.1. Seed of all species except *Chamaecytisus palmensis* was collected from the Midlands or the Midlands fringe. *Acacia* and *Chamaecytisus* seed was heat treated by pouring near-boiling water over the seed and allowing it to cool before draining. The heat-treated seed was then air dried and sown within a week of treatment. The results of seed viability tests, conducted by the Forestry Commission, Tasmania, are given in Table 2.1. Seed was bulked with bran, and sown at either 100 grams km^{-1} or 200 grams km^{-1} of sowing line.

Plots were monitored weekly for seedling emergence. No attempt was made to identify particular species. Rainfall, air maximum and minimum temperatures 10 cm above the ground, and soil temperatures at 5 cm depth and on the surface were also measured weekly. At each site, two soil samples were taken in late October, to analyse the atrazine content.

Residual analysis indicated heteroscedacity, and data were log transformed to remove this. Differences between treatments were determined by analysis of variance, which was done using the statistical package Statgraphics®.

Table 2.1 Number of seeds per kilogram of species sown in Midlands broadacre trials, and the percentage of seed from each species used in the sowing mix.

Species	Min Nº viable seeds kg^{-1}	% of seed mix	No viable seeds kg^{-1} seed mix*
Acacia dealbata (Link.)	37 000	12.5	4700
Allocasuarina littoralis (Salisb.)	254 000	5	12700
Allocasuarina verticillata (Dryand.)	245 000	5	12250
Chamaecytisus palmensis (L.)	287 000	10	28700
Eucalyptus amygdalina (Labill.)	27 000	10	2700
E. camaldulensis (Dehnh.)	471 000	10	47100
E. coccifera (Hook. f.)	143 000	10	14300
E. ovata(Labill.)	378 000	12.5	48400
E. pauciflora (Sieb. ex Spreng.)	45 000	12.5	5700
E. viminalis (Labill.)	145 000	12.5	18500

* figures refer to approximate numbers only

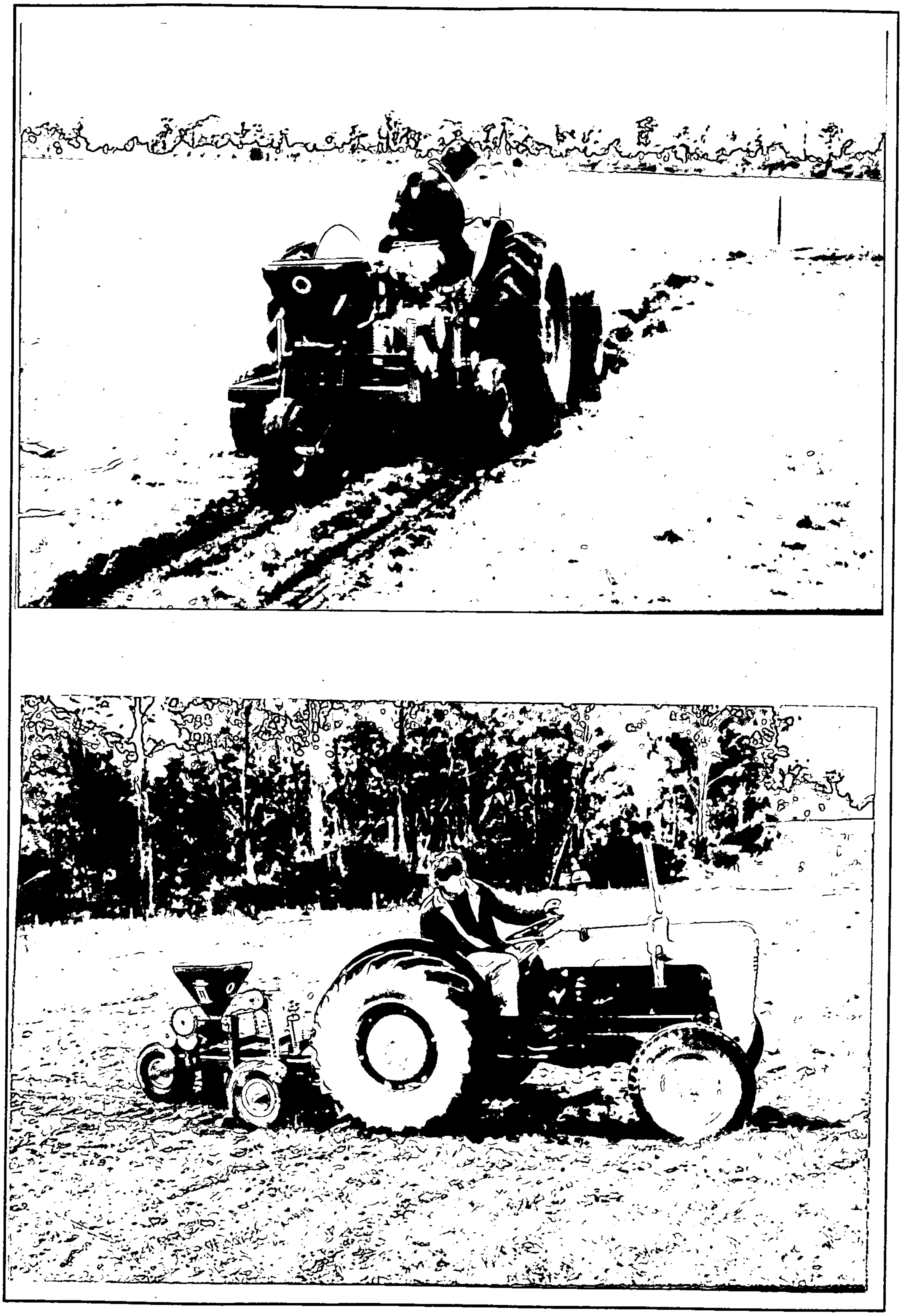

Figure 2.1. The Western Tree Seeder

Results

By November, germination had commenced at all sites. At Site 6, there were 1.2 seedlings metre^{-1} of sowing line (16% of viable seed sown) in November, which fell to 0.2 metre^{-1} (2.7% of viable seed) by March. At Site 4, there were 0.4 seedlings metre^{-1} (5.5% of viable seed) in November, which remained constant throughout the summer period. There were 0.9 seedlings metre^{-1} of sowing line (12.5% of viable seed) at Site 5 in November, which fell to 0.01 metre^{-1} (0.1% of viable seed sown) by March. This site was the only site with a sandy soil. There were no significant differences between treatments, including the two sowing rates, although at Site 5, strip application of glyphosate at the higher sowing rate resulted in significantly greater numbers of seedlings than in the control treatment (Tables 2.2, 2.3).

Glyphosate effectively controlled weeds until the end of November, when reinvasion occurred following spring rain. The combination of glyphosate and atrazine resulted in weed-free conditions throughout the summer, although this had no effect on seedling emergence or survival. One month after sowing, levels of atrazine in the soil averaged 1.5 ppm at Site 4, 0.1 ppm at Site 5, and 1.1 ppm at Site 6.

Climatic conditions recorded at the three sites are given in Tables 2.4, 2.5 and 2.6. In each table, the average conditions recorded at the closest Australian Bureau of Meteorology (ABM) monitoring station are included. Temperatures recorded 10 cm above the ground were greater than the standard ABM air temperature averages at all sites. Rainfall at Site 4 was below average in August, September, December, February and March; at Site 5 it was below average in August, October, December, February and March; and at Site 6 it was below average in August, September, December and February. In all other months, rainfall was above average at each site.

Table 2.2 Survival of emergents (pooled %) per metre of sowing line at three sites in the Midlands (site numbers correspond to those in Appendix 1).

Site	Survival of emergents (%)	
	2 months after sowing	6 months after sowing
Site 4	5.5	5.5
Site 5	12.5	0.1
Site 6	16.0	2.7

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Table 2.3. Average number of emergent seedlings 2 months after sowing for each treatment at each site. Numbers in brackets give confidence intervals. Different letters in the same column indicate treatment differences ($P<0.05$).

Treatment	Average Nº. seedlings metre^{-1} (Site 4)	Average Nº. seedlings metre^{-1} (Site 5)	Average Nº. seedlings metre^{-1} (Site 6)
Control	0.23^{a}	0.5^{b}	1.1^{a}
	(0.0 - 1.47)	(0.0 - 1.32)	(0.0 - 2.4)
Blanket glyphosate	1.00^{a}	1.5^{b}	1.1^{a}
200g seed km^{-1}	(0.0 - 2.2)	(0.7 - 2.29)	(0.0 - 2.4)
Strip glyphosate	0.0^{a}	1.5^{ab}	0.15^{a}
100g seed km^{-1}	-	(0.12 - 2.87)	(0.0 - 1.45)
Strip glyphosate	0.40^{a}	3.9^{a}	1.15^{a}
200g seed km^{-1}	(0.0 - 1.64)	(2.52 - 5.27)	(0.0 - 2.45)
Blanket atrazine	0.06^{a}	0.05^{b}	1.30^{a}
100g seed km^{-1}	(0.0 - 1.30)	(0.0 - 1.02)	(0.0 - 2.61)
Blanket atrazine	0.86^{a}	0.0^{b}	1.60^{a}
200g seed km^{-1}	(0.0 - 2.10)	-	(0.0 - 1.90)
Strip atrazine	0.20^{a}	0.06^{b}	0.60^{a}
100g seed km^{-1}	(0.0 - 1.44)	(0.0 - 0.86)	(0.0 - 1.90)
Strip atrazine	0.53^{a}	0.10^{b}	2.15^{a}
200g seed km^{-1}	(0.0 - 1.77)	(0.0 - 0.89)	(0.84 - 3.45)

Table 2.4. Climatic conditions recorded at Site 4 during the experiment.

Month	A	S	O	N	D	J	F	M
Rainfall (mm)	31.0	58.0	43.5	59.0	47.5	77.5	18.5	29.0
% Average rainfall*	64.5	124.2	69.9	121.1	80.2	188.6	45.6	75.1
Max air temperature(°C)	13.6	20.5	22.5	31.2	35.5	36.4	37.0	35.5
Min air temperature(°C)	-3.0	-2.7	-1.5	-2.2	4.5	1.8	1.5	-1.0
Soil temp surface(°C)	10.2	15.5	19.7	23.6	31.5	28.8	34.5	27.5
Soil temp 5 cm(°C)	8.0	10.3	14.7	17.4	21.5	22.4	22.0	18.5
Average rainfall (mm) *	49.5	50.8	64.3	51.1	60.7	39.8	42.7	33.5
Average max temp (°C) *	11.5	14.2	16.2	18.2	21.2	23.5	22.7	20.9
Average min temp (°C) *	1.2	2.7	4.7	6.1	7.7	8.5	8.9	7.4

* refers to average recordings at the ABM monitoring station, Campbell Town.

Table 2.5. Climatic conditions recorded at Site 5 during the experiment.

Month	A	S	O	N	D	J	F	M
Rainfall (mm)	20.0	22.0	81.0	70.0	16.3	56.7	10.0	27.0
% Average rainfall*	41.6	47.1	130.2	143.7	27.5	137.9	24.6	69.9
Max air temperature(°C)	15.0	19.6	19.3	28.4	33.5	33.6	36.0	34.5
Min air temperature(°C)	-3.0	-3.3	0.5	-1.4	4.0	0.4	-1.0	3.0
Soil temp surface(°C)	8.8	10.6	14.0	18.8	25.5	26.0	28.0	19.0
Soil temp 5 cm(°C)	7.2	5.0	10.0	13.2	18.0	16.8	18.0	14.5
Average rainfall (mm) *	43.6	41.9	54.3	47.0	58.0	31.2	39.3	34.3
Average max temp (°C) *	10.5	12.8	14.9	17.6	19.7	21.2	21.2	18.8
Average min temp (°C) *	1.7	2.9	4.2	5.6	7.2	8.1	8.2	6.8

* refers to average recordings at the ABM monitoring station, Oatlands.

Table 2.6. Climatic conditions recorded at Site 6 during the experiment.

Month	A	S	O	N	D	J	F	M
Rainfall (mm)	30.5	24.5	113.0	71.5	21.7	75.3	13.0	59.5
% Average rainfall*	63.4	52.5	181.6	146.8	36.6	183.2	32.0	154.1
Max air temperature(°C)	15.5	20.5	18.7	27.4	40.0	38.4	40.5	44.0
Min air temperature(°C)	-2.3	-1.5	-1.0	-1.6	3.5	0.8	1.5	4.0
Soil temp: surface(°C)	6.5	8.5	10.3	16.4	24.5	22.4	19.5	-
Soil temp: 5 cm(°C)	6.0	8.0	8.7	11.6	16.0	16.8	20.0	14.0
Average rainfall*	47	45	56	49	52	37	42	36
Average max air temp(°C)*	11.8	13.5	16.5	17.9	20.0	22.8	23.3	20.4
Average min air temp (°C)*	0.4	2.3	3.7	5.2	6.2	7.6	7.5	6.2

* refers to average recordings at the ABM monitoring station, Bothwell.

Experiment 2. Time of Sowing

Methods

A site was selected at 'Lovely Banks' (see Appendix 1 for site details), to investigate the effect of three times of sowing on the germination and survival of 15 species. The experiment was established as a randomised complete block design, with 15 blocks, three times of sowing and 15 species. Sowing took place on 27th July, 26th August and 29th September 1987.

The species included in the experiment were *Eucalyptus coccifera*, *E. gunnii* (Hook.f.), *E. viminalis*, *E. pauciflora*, *E. ovata*, *E. camaldulensis*, *E. tenuiramis* (Miq.), *E. rodwayii* (R. Baker & H.G. Smith), *Acacia dealbata*, *A. mearnsii* (De Wild.), *A. melanoxylon* (R. Br.), *Bursaria spinosa* (Sav.), *Allocasuarina verticillata*, *Banksia marginata* (Cav.) and *Chamaecytisus palmensis*. Local provenance seed was used for all species except *E. coccifera* and *E. gunnii* where seed was collected from dry sites on the Eastern Tiers, and *C. palmensis*, which was imported from the mainland.

Plots of one square metre, with a buffer of one metre, were marked in June. Immediately prior to sowing, the soil was scalped to a depth of 5 cm using a mattock, which removed the grass sward. Seed was sown at a rate of one gram per plot (approximately 10 kg ha^{-1}) for small seeded species, and two grams per plot (approximately 20 kg ha^{-1}) for large seeded species. Following sowing, the soil was lightly compressed. All *Acacia* and *Chamaecytisus* seed was heat treated prior to sowing, in the manner outlined in Experiment 1. There was no other seed treatment.

Seedling emergence, rainfall, maximum and minimum air temperatures 10 cm above the ground, soil temperatures at 5 cm depth, and soil matric potential were measured weekly throughout the experiment. Measurement of soil surface temperatures was initiated in February. Soil matric potential was measured using a Dewpoint Psychrometer (Wescor HR 33T). Mean emergence for each species and sowing time was determined, but due to the low rate of emergence, analysis of variance was not appropriate.

Results

There was very little emergence of any species at any time of sowing (Table 2.7). No emergence occurred at any sowing time until almost two months had elapsed, and there was no subsequent emergence in the following autumn or spring.

Although no specific data were collected, it was observed that weeds reinvaded all plots in November, regardless of the time of sowing. This coincided with heavy rains.

The weather conditions recorded during the experiment are detailed in Table 2.8. Rainfall was less than the average recorded by the ABM, and soil matric potential decreased from -0.25 in December to -1.7 in January, then -3.2 in February. While the data are incomplete, soil surface temperatures were greater in February and March than the maximum air temperature 10 cm above the ground.

Ants were observed browsing at this site, and seed from remnant *E. pauciflora* trees was found in excavated ant nests. It can be assumed that at least some of the sown seed was removed by ants.

Table 2.7. Mean number of emergent seedlings present per species 2, 3 and 6 months after sowing, for 3 sowing times (numbers in brackets refer to the percentage germination of each species).

Species	Nº seedlings present 2, 3 and 6 months after sowing at 3 times								
	27th July			26th August			29th September		
	2	3	6	2	3	6	2	3	6
Acacia dealbata	0	0.33 (4.0%)	0	0	0	0	0	0	0
A. mearnsii	0.33 (0.4%)	0.33 (0.4%)	0	0	0	0	0	0	0
*A. melanoxylon**	0	0.2	0	0	0	0	0	0	0
Allocasuarina verticillata	0.06 (0.2%)	0	0	0	0	0	0	0	0
*Banksia marginata**	0	0.13	0	0	0	0	0	0	0
*Bursaria spinosa**	0.06	0	0	0	0	0	0	0	0
Chamaecytisus palmensis	1.33 (23%)	2.0 (34%)	0	0.06 (1.0%)	0.13 (2.0%)	0	0	0.06 (1.0%)	0
Eucalyptus camaldulensis	0	0	0	0	0.13 (0.2%)	0	0	0.06 (0.1%)	0
E. coccifera	0	0	0	0	0.06 (0.4%)	0	0	0	0
E. gunnii	0	0	0	0.06	0	0	0	0	0
E. ovata	0.53 (1.0%)	0.33 (0.8%)	0	0	0	0	0	0	0
E. pauciflora	0	0	0	0	0	0	0	0	0
E. rodwayii	0.33 (0.7%)	0.26 (0.6%)	0	0	0	0	0	0	0
E. tenuiramis	0.26	0.20	0	0	0	0	0	0	0
E. viminalis	0	0.13 (0.8%)	0	0	0	0	0	0	0

* results of viability tests were not available.

Table 2.8. Climatic data recorded at 'Lovely Banks' during the time of sowing experimental work.

Month	A	S	O	N	D	J	F	M	A	M
Rainfall (mm)	7.9	32.3	29.5	64.5	20.5	22.6	23.3	12.7	11.5	47.1
% average rain*	18	78	53	128	36	51	67	30	22	98
Maximum air temp(°C)	11.5	19.8	20.5	28.5	26.7	33.3	32.6	31.3	25.0	20.5
Minimum air temp(°C)	-4.0	-1.7	2.0	2.3	2.7	4.3	-0.4	0.75	-1.0	2.5
Soil temp surface (°C)	-	-	-	-	-		38.6	34.3	24.9	15.0
Soil temp 5 cm depth (°C)	8.0	10.5	13.7	17.3	18.5	23	21.8	19.5	15.5	12.5
Soil matric potential (MPa)(unripped)	-0.18	-0.43	-0.13	-0.15	-0.24	-1.7	-3.2	-4.4	-3.0	-
Soil matric potential (MPa)(ripped)**	-	-0.29	-0.11	-0.08	-0.19	-0.81	-4.3	-3.1	-3.3	-
Average rainfall (mm) *	43.6	41.9	54.3	47.0	58.0	31.2	39.3	34.3	67.0	56.0
Average max temp (°C) *	10.5	12.8	14.9	17.6	19.7	21.2	21.2	18.8	15.3	12.1
Average min temp (°C) *	1.7	2.9	4.2	5.6	7.2	8.1	8.2	6.8	10.1	7.6

* refers to averages recorded at the ABM monitoring station at Oatlands.
** data applicable to Experiment 3 only.

Experiment 3. Effects of Soil Preparation on Seed Germination and Seedling Survival

Methods

The experiment was established in 1987 at 'Lovely Banks' (see Appendix 1 for site description), as a completely randomised design with two replicates of each of three treatments ('ripped soil', 'scalped soil', and 'control'). The site was fenced with chickenwire to exclude domestic stock and rabbits, and an electric outrigger was added for protection from possum browsing. Plots of 20 x 20 metres were then marked. Deep ripping and soil scalping were done in May, using a D6 bulldozer. Plots were deep ripped to a depth of 60 - 90 cm using a winged ripper, and soil was then smoothed over the riplines using two offset cultivation discs. Where scalping was a treatment, the top 5 cm of soil was removed. As a control, soil was left uncultivated. Glyphosate was applied to all plots in late July, at a ratio of 50:1 water to herbicide and a rate of 8 litres ha^{-1}. Excellent sward elimination was achieved, and at the time of sowing in September, 90 - 100% of the soil remained weed free.

Sowing was done with a Western Tree Seeder, which is described in Experiment 1. Equal weights of *E. pauciflora*, *E. ovata*, *E. viminalis*, *E. amygdalina*, *A. dealbata*, *B. spinosa* and *C. palmensis* seed were sown at a collective rate of 50 grams 100 metres^{-1} of sowing line, which was equivalent to 2.5 kg ha^{-1}. Sowing lines were spaced at one metre intervals. Local provenance seed was used for all Midlands species. The *Acacia* and *Chamaecytisus* seed was heat treated as described in Experiment 1.

Plots were monitored weekly for germination. Rainfall, maximum and minimum air temperatures at 10 cm height, soil temperatures at 5 cm depth and soil matric potentials were recorded weekly. Matric potential was estimated for ripped and unripped soil. Measurement of surface soil temperatures was initiated in February.

The number of seedlings per plot was measured. Residual data analysis revealed heteroscedacity, and data were log transformed to overcome this, after which analysis of variance was performed using the computer package Statgraphics ®.

Results

Two months after sowing, there were no significant differences in the number of seedlings in each ground preparation treatment (Table 2.9). After both 4 and 7 months, plots which had been scalped averaged more seedlings than the control, although the difference was not significant after 7 months. Seven months from sowing, plots which had been deep ripped had significantly less seedlings than plots which had been scalped (Table 2.9). The average number (pooled) of seedlings per metre of sowing line was 0.7 in November (0.6% of viable seed), which decreased to 0.1 per metre after 7 months.

Climatic details are summarized in Table 2.8. Rainfall throughout the experiment was consistently lower than average, except in November. In February and March, soil surface temperatures were greater than the air temperature 10 cm above the ground, which in turn was greater in all months than the average temperature recorded at standard height by the Australian Bureau of Meteorology (Anonymous 1972). The soil in ripped ground was moister than in unripped ground in all months except February.

It was observed that the length of weed control differed between treatments. Glyphosate effectively controlled weeds until heavy rains in November, when weed species began to grow prolifically. As glyphosate was the main form of weed control in the ripped plots, these were also rapidly covered with weeds. The scalping treatment, however, provided a weed-free environment for 8 to 12 months, suggesting the weed seed bank had been effectively eliminated.

Ants were prevalent on this site, and seed of local remnant *E. pauciflora* was found in excavated ant nests, suggesting that browsing of the sown seed may have contributed to the results.

Table 2.9. Mean number of seedlings per plot for the 3 ground preparation techniques at Lovely Banks. Different letters in columns indicates treatment differences

Treatment	Number of months since sowing		
	2	4	7
Control	110 ^{a}	10 ^{b}	16 ^{ab}
	(26 - 194)	(0 - 10)	(11 - 21)
Deep rip	40 ^{a}	25 ^{ab}	12 ^{b}
	(25 - 54)	(10 - 40)	(9 - 15)
Scalp topsoil	25 ^{a}	30 ^{a}	20 ^{a}
	(4 - 46)	(20 - 40)	(17 - 23)

Experiment 4. Use of a Cover Crop to Provide Shelter to Emerging Seedlings in the Midlands.

Methods

The experiment was established in 1988 at 'The Square' (see Appendix 1 for site description) as a completely randomised block design, with three treatments replicated twice. The treatments included strip application of glyphosate, blanket (total) application of glyphosate (control treatment), and the sowing of a cover crop. The site was fenced to exclude domestic stock, and plots of 20 x 40 metres were marked. Glyphosate was then applied, at a rate of 5 litres ha^{-1} and a ratio of 50:1 water to herbicide. Plots to be sown with a cover crop were totally sprayed with glyphosate prior to sowing, and then cultivated after the sward had died. Where strips of herbicide were applied, they were spaced 0.5 metres apart.

A cover crop of ryecorn, a non-fertile hybrid grass species, was sown in rows into the cultivated ground in September, at a rate of 2.5 kg ha^{-1}. On the same day, a mix of *E.*

camaldulensis, *E. viminalis*, *E. ovata*, *E. pauciflora*, *E. coccifera*, *E. amygdalina*, *A. verticillata*, *C. littoralis*, *A. dealbata* and *C. palmensis* was sown between rows of ryecorn, and into the control and strip herbicide treatments. Details of the sowing mix are given in Table 2.1. The seed was bulked with bran and sown at a rate of 100 grams per 100 metres of sowing line, using the Western Tree Seeder. Seedling emergence was monitored weekly. Rainfall, maximum and minimum air temperatures 10 cm above the soil surface, and soil temperatures were also measured weekly. Emergence data were log transformed to remove heteroscedacity, and analysis of variance was performed using Statgraphics®.

Results

The cover crop germinated and grew rapidly, providing an effective screen for sowing lines. Ryecorn plants reached approximately 1.5 metres height. None were present within 0.25 metres of each line sown with native tree seed. The areas sprayed with glyphosate remained weed-free until mid-November, when a gradual re-invasion commenced, coinciding with above-average rainfall in October and November (Table 2.11). Vegetation left by the strip herbicide application, which it was thought would grow rapidly and provide low shelter to the sowing lines, grew very slowly and provided virtually no shelter.

Tree seed commenced germination in mid-October. By the end of November, there was an average (pooled) of 0.5 seedlings metre^{-1} of sowing line, which was equivalent to 6.9% of viable seed sown. However, this rapidly decreased, and by the end of December no seedlings remained. Sowing a cover crop did not affect the number of emergents, although strip application of glyphosate resulted in significantly less seedlings per metre than the control treatment (Table 2.10).

Rainfall during the period of the experiment was well above-average in all months except September and December. Maximum air temperatures 10 cm above the ground were close to 40°C in December, January and February, and minimums were below zero leading up to December. The greatest differences between maximum and minimum terperatures occurred between December and February (Table 2.11).

Table 2.10. Mean number of seedlings per metre of sowing line measured at 'The Square'. Different letters indicate treatment differences ($P<0.05$).

Treatment	Months since sowing		
	1	2	3
Control	0	0.5^{a} (0.04-1.0)	0
Glyphosate-strip	0	0.2^{b} (0.01-0.3)	0
Cover crop	0	0.9^{ab} (0.2-1.56)	0

Table 2.11. Summary of climatic data recorded at 'The Square'.

Date	S	O	N	D	J	F
Rainfall (mm)	24.5	113	81	17.3	58.5	55.5
% average rainfall*	52	181	166	29	142	136
Max air temp (°C)	20.5	18.7	27.4	40	38.4	37.5
Min air temp (°C)	-1.5	-1.0	-1.6	3.5	0.8	0
Surface soil temp(°C)	8.5	10.3	16.4	23.5	22.6	23.5
Soil temp 5cm(°C)	8.0	8.7	11.6	15.5	16.0	16.5
Average rainfall (mm) *	43	52	45	42	25	34
Average max temp (°C) *	13.5	16.5	17.9	20.0	22.8	23.3
Average min temp (°C) *	2.3	2.7	5.2	6.2	7.6	7.5

* refers to averages recorded at the nearest ABM monitoring station (Bothwell).

Experiment 5. Effects of long term weed control on the growth and survival of direct-sown eucalypt seedlings.

Methods

Previously direct-sown sites were used for this experiment which was established in 1987. They were located on the properties 'Lovely Banks' (Site 2), 'Wyndham' (Site 8) and 'Wetheron' (Site 6) (site numbers correspond with those in Appendix 1), all of which had been direct sown two years previously. Two treatments were applied at each site, in a completely randomized design. The treatments were: (1) control (no treatment); and (2) overspray with Fusilade®, a highly active post-emergent selective herbicide that controls both annual and perennial grasses, which can be sprayed over a wide range of broadleaf species without inducing phytotoxic effects (Ashton and Crafts 1981).

The sample size at each site varied, and was dependent on the number of seedlings present. At Site 2, 50 *E. ovata* seedlings were pegged per treatment. At Site 8, 15 seedlings of *E. ovata* were allocated to each treatment, and at Site 6 there were 30 *E. ovata* seedlings per treatment.

Each seedling in the overspray treatment had Fusilade® applied around its base for a radius of 0.5 metres. The Fusilade® was applied by knapsack at a rate of 2 litres ha^{-1}. It was mixed with the wetting agent Agral 60®, which was added at a rate of 45 mls per 15 litres of water. Seedling heights were measured immediately prior to the herbicide application, and again 2 and 6 months after application. The percentage of grasses and broadleaves in the weed sward in a 0.5 metre radius around each seedling was estimated by eye prior to herbicide application. The total percentage weed cover was also estimated, by determining the approximate area of weed species covering a given soil surface area.

Seedling height increments 2 and 6 months after spraying were calculated, and differences between treatments were established by analysis of variance. The computer package Statgraphics® was used for the analysis.

Results

The effectiveness of Fusilade® in controlling weeds was dependent on the percentage grass present around each seedling. The greater the percentage of grasses present, the greater was the weed control, as would be expected when using a grass-specific herbicide. Fusilade® was effective in eliminating all grasses present around seedlings.

There were differences in the percentage of grasses present in the weed mix at each site, as illustrated in Table 2.12 This can be related to differences observed between treatments at each site. At Site 2, where the percentage weed cover was lowest, and grass was not a major component of the weed species mix, overspraying with Fusilade® had no significant effect on seedling height increment. At Site 6, where the percentage total weed cover was greater, although grasses were not a major component, overspraying with Fusilade® increased average seedling height increment ($P<0.05$) by 22% after 2 months and 14% after 6 months (Table 2.13). Grasses were the main component of the weed species present at Site 8, and the total percentage weed cover at this site was very high. Overspraying with Fusilade® increased average seedling height increment by 51% after 2 months and 69% after 6 months ($P<0.05$).

No phytotoxic effects were observed on any eucalypt seedlings from the application of Fusilade®.

Table 2.12. Number of seedlings in each percentage grass cover category, expressed as a percentage of the total seedlings monitored at each site. Included in the table is an estimation of the average total weed cover around seedlings at each site. Grass cover was estimated prior to herbicide application.

Site	Nº seedlings in grass cover classes prior to herbiciding (% of total number of seedlings at each site)				average %total weed cover
	< 25% grass	26 - 50% grass	51 - 75% grass	> 75% grass	
Site 2	13	41	38	8	60
Site 6	60	20	8	12	75
Site 8	0	11	3	86	90

Table 2.13. Average seedling height increment for weed control treatments applied at 3 sites in the Midlands. Different letters in the same column indicate treatment differences.

Site	Treatment	Average height (cm)	
		2 months	6 months
Site 2	Control	6.4^{cd} (3.6-9.2)	10.3^{c} (9.0-11.6)
	Overspray	6.5^{cd} (3.6-9.4)	11.1^{c} (9.7-12.5)
Site 6	Control	6.9^{d} (6.2-7.0)	8.6^{d} (8.5-8.6)
	Overspray	8.6^{c} (8.5-8.7)	11.5^{c} (11.4-11.5)
Site 8	Control	11.2^{b} (10.4-12.2)	14.4^{b} (12.5-16.3)
	Overspray	23.2^{a} (22.1-24.3)	33.7^{a} (31.8-35.6)

Summary of Results

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* Mechanical soil scalping and the use of residual herbicide provided a longer weed-free period than did knockdown herbicide (Tables 2.3, 2.9).
* Mechanical scalping increased seedling numbers after 4 but not 7 months (Table 2.9), whereas residual herbicide application had no effect on seedling numbers (Table 2.3).
* Scalping by hand provided a much shorter weed-free period than did machine scalping.
* Controlling weeds in the vicinity of established direct-sown seedlings increased seedling height (Table 2.13).
* Earlier time of sowing resulted in greater emergence, but had no effect on survival (Table 2.7), which may have been related to weed competition during the summer period.
* Sowing a cover crop had no effect on seedling emergence or survival (Table 2.10).
* Survival was poorer on sandy sites (Table 2.3), suggesting that such sites may be inappropriate for direct seeding.
* Sowing rates greater than those used appeared to be required to give adequate stocking rates or experimental results in which treatment effects could be meaningfully compared.
* Weather conditions recorded throughout the experiments were harsh, and may have contributed to experimental results (Tables 2.4, 2.5, 2.6, 2.8, 2.11).

Discussion

Weed control

Many authors have reported increased germination and survival with better weed control (eg Dalton 1990; Bird *et al.* 1990). In the present experiments, mechanical soil scalping, which increased weed control, resulted in greater seedling numbers after four but not seven months (Table 2.9). It is possible that, while long term weed control was achieved with this technique, seedlings were more vulnerable to temperature extremes and desiccation. Sheldon (1974) and Harper (1977) both discuss the importance of microsite variability in harsh environments, and scalping may have been more effective if it had been followed by rough cultivation.

Application of residual herbicide did not affect germination or survival (Table 2.3), even though good weed control was achieved. Although there were still quantities of atrazine in the the soil at the time of sowing, this did not appear to detrimentally affect emergence. The persistence in the soil of chemicals such as atrazine depends principally on microbial activity, which is related to factors such as temperature, pH, soil moisture content, nutritional status and soil texture (Hallett 1983). Concentrations may therefore have been patchy, with germination associated with areas of low or no herbicide concentration. Patchy germination was certainly observed, although it appeared to be a general phenomenon rather than one associated with a particular herbicide treatment. The application of residual herbicide, and the consequent bare earth, may have exposed seedlings to temperature extremes and drought without providing appropriate microsite variability. Rough cultivation prior to application of residual herbicides may have enhanced results.

The control of weeds in the vicinity of eucalypt seedlings was demonstrated to increase mean seedling height (Table 2.13). Experimental results suggest that both broadleaf and grass species were exerting a competitive effect, although grass competition appeared to be more significant than broadleaf competition. Similarly, Gordon *et al.* (1989) found that grass competition had a more negative effect on the growth of *Quercus douglasii* than did competition from a broadleaf species.

More effective long term weed control was achieved in the first experiment by spraying residual rather than knockdown herbicides. Mechanical soil scalping was also found to considerably lengthen the weed free period, which was probably related to a reduction in the number of weed seeds at or near the scalped soil surface (Ball and Miller 1990). In a practical context, soil scalping is not suited to all sites, and particularly to those prone to erosion. Use of residual herbicides may affect germination of sown seed on some sites, depending on soil type, rainfall and time of application (Hallett 1983; Venning 1988; Dalton 1990).

Soil scalping in conjunction with the time of sowing experiment resulted in a much shorter period of weed control than did mechanical scalping, which my have been related to the proximity of seed-bearing weed species to the hand scalped plots. While buffers of one metre were placed around these plots, this may not have been sufficient to overcome re-seeding by weeds. Alternatively, hand scalping may not have removed all soil-stored seed. This is unlikely, as plots were scalped to a depth of 5 cm, which effectively removed the soil stored seed bank when mechanical scalping was conducted to the same depth at the same site.

Fusilade® has obvious limitations as a chemical for controlling weeds which germinate around seedlings following planting or sowing, being only useful where grasses are the main competitors. Other chemicals may be more suitable. Bird *et al.* (1990) investigated a range of chemicals which may be suitable for overspraying eucalypt seedlings growing in pasture, and found that the triazines (Simazine®, Propazine®, atrazine), which are pre-emergent residual herbicides, were the most effective. They also experimented with a wide range of knockdown herbicides such as glyphosate, amitrole and Sprayseed®, which tended to cause seedling scorch and growth depression, but still increased survival. Wilkinson and Neilsen (1990) investigated the effect of post-planting applications of atrazine on eucalypt seedling survival and growth, and found that such applications significantly reduced the survival of paper pot seedlings but did not affect the survival of larger, older, open-rooted seedlings, suggesting that seedling age or size is an important determinant of overspraying effects.

Time of Sowing

In these experiments, most sowing was conducted in spring, although in Experiment 2 winter sowing was also investigated. In the Midlands there have been problems previously reported with autumn and winter sowings (Geard 1986; 1987). Dry soil conditions are often not alleviated until winter, making weed control difficult. Soil moisture contents are often very low in autumn, and there is the possibility of light rainfalls stimulating the germination of sown seed without follow up rains to ensure survival. Broadscale winter sowings are a problem on many sites, where soils may be boggy and inaccessible to machinery until August. When sowing in early spring, however, effective weed control can usually be achieved, soil moisture content is high, soil temperatures are rising, and the possibility of frosts is lower than in winter.

In Experiment 2, the earliest time of sowing (winter) was found to result in the greatest percentage seedling emergence (Table 2.7). This, however, had no apparent impact on survival. The climatic conditions throughout the experiment were particularly unfavourable for germination and survival of small seedlings, which may explain this result. It is also possible that weed reinvasion in November and subsequent competition for resources contributed to mortality.

The species which germinated after the first sowing were almost exclusively different from those germinating after subsequent sowings. Different species germinate under different temperature conditions, and some require cool-moist stratification before germination will commence (Boland *et al.* 1980; Langkamp 1987). Langkamp (1987) lists optimum germination temperatures for a range of species, and the temperatures considered optimum for the species sown in these experiments suggest that temperature was not a major factor. Of the species sown, Boland *et al.* (1980) and Turnbull and Doran (1987) consider only *E. pauciflora* to require cool moist stratification prior to germination. Thus, lack of such a treatment is unlikely to account for the differences. Moisture availability has generally been found to be a major factor influencing seed germination (Edgar 1977; Bachelard 1985; Gibson and Bachelard 1987). Different species may be more able to cope with low levels of available soil moisture (Bachelard 1985), or with moisture fluctuations. At the earliest sowing time, high soil moisture levels were probably maintained for longer periods after rainfall events than at later sowing times, due to a reduced evaporation rate. Average evaporation recorded at Oatlands is 3.8 cm in August and 7.8 cm in November (Anonymous 1972), and relative humidity in this period decreases by an average of 15%. High rainfall in November may not have increased germination because of low effectiveness.

Soil Preparation

No soil preparation technique affected emergence, although survival was increased after four months by scalping (Table 2.9). Sowing into untreated rather than smoothed riplines may have produced more favourable results in this treatment, as the riplines would have provided more protection from temperature extremes and desiccation than could be expected from a smoothed surface. Soil scalping also prepares a smooth sowing surface.

The Western Tree Seeder may be an inappropriate machine for direct seeding on difficult to regenerate sites, as it prepares a smooth furrow approximately 10 cm wide by 1 cm deep, providing little microsite variability. Broadcast sowing onto a roughly prepared surface may be more appropriate.

Cover Crop

Sowing a cover crop did not affect emergence or survival of tree seed sown in the Midlands environment (Table 2.10), although the cover crop itself established well. Burns (1987) also found that germination was not affected by the presence of a cover crop, but he measured increased seedling survival. In the present experiment, it is possible that the sowing rate of 2.5 kg ha^{-1} was inappropriate. Burns (1987) found that increasing the rate of Japanese millet from 2 kg to 20 kg ha^{-1} increased the gravimetric soil moisture content and reduced wind velocity. However, other species used as cover crops may compete with direct sown seedlings (Clemens 1984).

Site

Survival was less on sandy sites compared to sites with heavier soil. This may have been related to the more rapid drying of sandy soils, or to sandblasting of seedlings in windy conditions. Geard (1987) reported similar problems on sandy soils in the Midlands. It may be that direct seeding is more appropriate for sites with heavier soil types.

Weather

The results of these direct seeding trials may have been influenced by difficult weather conditions. Often rainfall was lower than the average for the area, and air temperatures 10 cm above the ground were extreme. In many instances, the weather data suggested harsher than normal conditions, but even when the data closely approximated average figures, seed emergence and survival was often poor. Variability in soil moisture may have been particularly important, although temperature extremes have been found by other authors to cause tissue damage in seedlings (Cunningham 1960; Nobel 1984). It is possible that much of the Midlands environment experiences climatic conditions which, without site modification in some form, will result in poor establishment of tree and shrub species. Similar problems have been experienced in high altitude and lowland dry eucalypt forests in Tasmania (Battaglia 1990a; 1990b). Battaglia (1990a) concluded that establishment of *Eucalytus delegatensis* was dependent on seasonal variation in climate, with the timing of frosts and rainfall events being particularly critical at the margins of its distribution at high altitudes and on dry sites.

Sowing Rate

In many of the experiments outlined previously, percentage germination was relatively high, but the number of seedlings per metre of sowing line was low, suggesting that the sowing rates used were too low, particularly for experimental evaluation. In addition, long-term survival was generally much lower than the 1% cited by Venning (1988). Using Venning's figure, it can be estimated that, to establish *E. amygdalina* with a viability of 230 000 seeds kg^{-1}, and aiming for 2500 stems per hectare, one kilogram of seed would be required. However, rates of at least double this were sown in the present experiments, with unacceptable numbers of survivors. This suggests that much higher sowing rates may be necessary. The economic advantages of direct seeding become more tenuous as greater sowing rates are required.

Conclusions

From the results of these trials, direct seeding could not be considered successful on a range of Midlands sites. A number of factors were identified as contributing to the poor results, including soil type, weed control, time of sowing, sowing rate and weather conditions. To investigate in detail some of the factors contributing to poor field results, the work detailed in Section B was initiated.

Figure 2.2. Broadacre field plot 'Fosterville', located near Campbell Town. The site has been recently sown.

Figure 2.3. Broadacre field plot 'Wetheron', located near Bothwell. Illustrated is the effect of strip application of atrazine, three months after sowing (December).

Section B

FIELD AND GLASSHOUSE EXPERIMENTAL WORK

CHAPTER 3. An investigation of the effectiveness of common techniques used to aid establishment.

Introduction

In the broadacre field trials discussed in the previous chapter, the effect of different treatments on emergence, survival and growth were often unclear. This was due to a number of factors. The size and number of trial sites, and the distance between sites, created problems with intensive monitoring. The number of species sown at each site was large, which made it difficult to monitor individual species responses, due mainly to the sheer size of this task. While percentage emergence was in most cases acceptable, the number of emergent seedlings per metre of sowing line was often very low, and many of the treatment effects appeared to be masked by weather conditions or experimental noise. It was determined that direct seeding was not particularly successful at any site, but the factors influencing results were unclear.

The experiment described in this chapter was established with the aim of explaining the effects of soil moisture content, fertilizer, weed control and mulch on the emergence, survival and growth of three eucalypt species. To do this, a small factorial experiment was established and intensively monitored. Half of all plots were irrigated, so that the effects of high and low soil moisture levels could be evaluated. Fertilizer was added at the time of sowing to some plots, to determine whether this would enhance establishment. Mulch was applied as a treatment to increase microsite heterogeneity. The effects of no weed control, initial weed control and long term weed control were explored. The sowing rate was purposefully very high, and calculated to achieve a minimum of 20 emergents per sub-plot. It was hoped that this, combined with a high degree of replication, would allow comparison of the effect of treatments on the short and long term establishment of the three species.

Methods

In July 1989, 50 x 25 metres of land on the Tasmanian University farm at Cambridge (see Appendix 1 for site description) was ploughed to a depth of approximately 20 cm, and fenced with chicken wire. The experiment was established as a completely randomised split block design, with 3 blocks down the slope and 2 blocks across-slope, and 2 irrigation (+, -), 3 weed control (none, initial and long term), 2 mulch (+, -) and 2 fertilizer (+, -) treatments. Treatments were replicated 12 times. The experiment was completely factorial, except in the allocation of fertilizer and mulch treatments, which were apportioned as follows:

-no weed control ± fertilizer addition;
-initial weed control ± fertilizer addition;
-initial weed control ± mulch;
-long term weed control ± mulch.

Within the wire enclosure, an area of 21 x 40 m was pegged and divided into three blocks down the slope, each of which was seven metres wide. Within each block, twenty 4 m^2 plots were pegged, each buffered from the adjoining plot by a one metre strip. Each 4 m^2 plot was divided into four 1 m^2 sub-plots, and the boundaries were marked with string. The site was then blocked twice across the slope, and within each of these blocks, the two irrigation treatments were randomly allocated. Irrigation and weed control treatments were allotted at the plot level, and mulch and fertilizer treatments at the sub-plot level. Figure 3.1 illustrates the site layout.

In plots where irrigation was to be applied, 13 mm plastic pipe was run down the slope, and one Turbokey® dripper (capacity four litres $hour^{-1}$) was placed in the centre of each 1 m^2 sub-plot. These lines of plastic pipe were joined to a main line which was fed from an adjacent dam by an electric pump.

In mid-August, all plots in initial or long term weed control treatments were sprayed with glyphosate, at a ratio of 50:1 water to herbicide, and a rate of 8 litres $hectare^{-1}$. By the end of August, there was complete sward kill, which lasted in the initial weed control treatment plots for approximately two months, with six months elapsing before there was total sward recovery. Long term weed control was conducted by applying glyphosate with a wickwand, at monthly intervals. Following sowing, coarse woodchips were spread over those subplots in mulching treatments, covering approximately 50% of the surface area.

In early September, three weeks after spraying, *Eucalyptus pauciflora, E. amygdalina* and *E. ovata* seed was sown, at rates of 4.70, 1.85 and 0.15 grams $metre^{-2}$ respectively, the amount of seed calculated from Forestry Commission, Tasmania germination tests to give approximately 100 viable seeds per species (a pooled species equivalent of 22 kg ha^{-1}). Subsequent viability tests (Appendix 2) indicated that the number of seeds sown was more equivalent to 580, 460 and 150 viable seeds under laboratory conditions. These figures were used when converting emergence data to percentages. The provenances used and the germination characteristics of each species are detailed in Appendix 2.

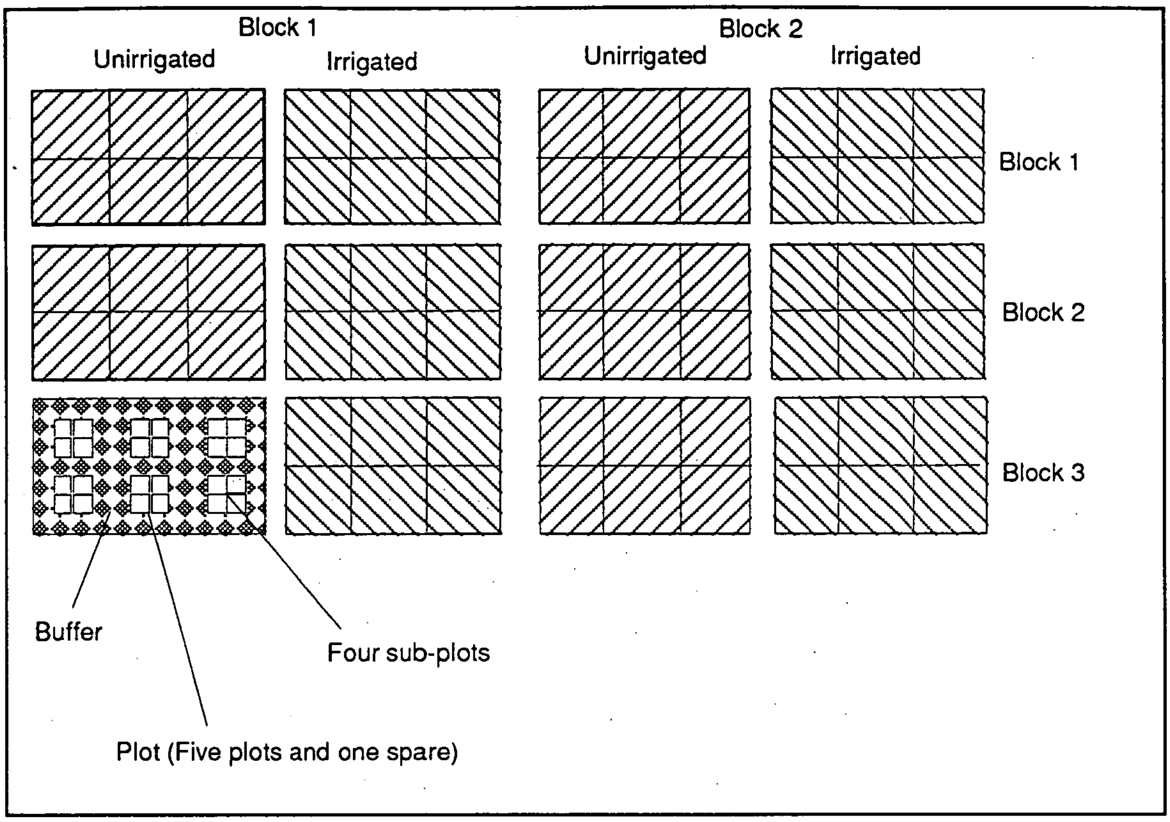


Figure 3.1. Plot layout at the Cambridge field site.

Following sowing, NPK 8:4:10 fertilizer was added to those sub-plots in fertilizer treatments, at a rate of 20 grams m^{-2} (equivalent to 200 kg ha^{-1}), the rate recommended by Duckett (1987) for fertile sites.

Irrigated plots were given approximately two litres of water at dawn and dusk each day. Irrigation ceased in May. In late November, gravimetric soil water content was measured by taking soil samples from spare plots at upper, mid and lowerslope positions (two replicates each), in both irrigated and unirrigated plots. Ten samples were removed from each site, with two taken from the centre of each plot, and pairs of samples taken progressively across the slope towards the plot boundary. The samples were collected using 5 cm diameter x 10 cm deep metal rings, which were pressed into the ground to a depth of 11 cm, removed and placed into plastic bags and an esky for transportation to the laboratory. Once in the laboratory, samples were weighed while still in the metal rings, and then oven-dried in the rings at 60°C until their weights were constant (approximately

48 hours). Gravimetric soil moisture content was then estimated, using the following formula:

$$\text{Gravimetric } H_2O \text{ content} = \frac{\text{weight wet soil - weight dry soil}}{\text{weight dry soil}} \times 100$$

Seedling emergence and survival were monitored fortnightly for 3 months, and then monthly for 4 months and finally at 12 months from sowing. Cocktail toothpicks, painted a different colour for each species, were placed next to emergents to enable identification of individuals. When a seedling died, the toothpick was removed. Cumulative emergence and survival were estimated for the 12 month period. The height of the tallest seedling of each species per subplot was measured at 6 monthly intervals. Rate (speed) of emergence was estimated by calculating the number of days take to achive a given percentage of final emergence.

Air maximum and minimum temperatures at 10 cm height, and rainfall, were monitored at fortnightly intervals between September and March, and compared to the climatic data measured at the nearby Hobart Airport Australian Bureau of Meteorology monitoring station. As well, soil temperatures at the surface and 5 cm depth during the course of a day were measured fortnightly during October, the period when maximum germination occurred.

Residual analysis indicated heteroscedacity, and all data were log transformed prior to analysis to overcome this. The data were split into 5 fully factorial experiments, on which analysis of variance was conducted using the General Linear Model procedure in SAS, which uses the method of least squares to fit general linear models and is appropriate for unbalanced data sets (SAS Institute Inc 1989a, b).

Results

Gravimetric Soil Moisture Content

The gravimetric soil moisture content in November was greater in irrigated than unirrigated subplots (Table 3.1). Gravimetric soil water content was greatest in the centre of irrigated subplots, which was the area closest to the drippers, and progressively decreased towards the subplot boundary (Table 3.2). There was little variation in gravimetric soil water content within unirrigated subplots. The water content was less in lowerslope subplots than in midslope or upperslope subplots (Table 3.1).

Table 3.1. Gravimetric water content (%) of soil samples taken in irrigated and unirrigated subplots at Cambridge in November.

Treatment	Gravimetric Soil water content (%)		
	Upperslope	Midslope	Lowerslope
Irrigated	12.14	15.35	13.22
Unirrigated	11.90	11.10	7.14

Table 3.2. Variation in gravimetric soil water content (%) from the centre to the edge of irrigated an unirrigated subplots at Cambridge.

Location Within Subplot	Gravimetric Soil Moisture Content (%)	
	Irrigation	No Irrigation
Centre	17.4	9.7
Middle	13.5	9.8
Edge	10.6	10.6

Climatic Conditions

Rainfall recorded at the Cambridge field site between October and March closely approximated that recorded at the Hobart airport weather station. For this reason the monthly rainfall recorded at both sites is presented in Figure 3.2. There were only 3 months throughout the experiment when the rainfall recorded at Hobart airport was not below average (Anonymous 1975) (Table 3.3).

Table 3.3. Percent of average annual rainfall recorded at Hobart airport for the duration of the Cambridge field experiment.

Month	A	S	O	N	D	J	F	M	A	M	J	J	A
%average rainfall*	88	58	173	26	78	47	95	56	53	33	54	208	154

* refers to averages recorded at the ABM monitoring station (Hobart Airport)

Figure 3.3 presents the highest maximum and the lowest minimum temperatures recorded from November to March, and compares them to the maximum and minimum temperatures recorded at Hobart airport under standard conditions. The temperatures recorded at Hobart airport were close to the average recorded over a number of years at the same station (Anonymous 1975). The maximum and minimum air temperatures measured 10 cm above the ground were much greater than those measured under standard conditions. The number of frost days recorded at Hobart airport are presented in Figure 3.4.

Soil temperatures were measured throughout the day on two occasions. The soil surface is vulnerable to dramatic fluctuations in temperature, in response to cloud cover and time of day. Geiger (1966) considers that, to obtain an accurate measurement of fluctuations in soil temperature, many readings need to be taken simultaneously from a number of sites. However, the measurements taken in this experiment give some indication of the temperatures experienced by germinating seeds and emergent seedlings. There was less variation in the temperature at 5 cm depth than at the surface. Temperatures were lower at depth than at the soil surface (Figure 3.5).

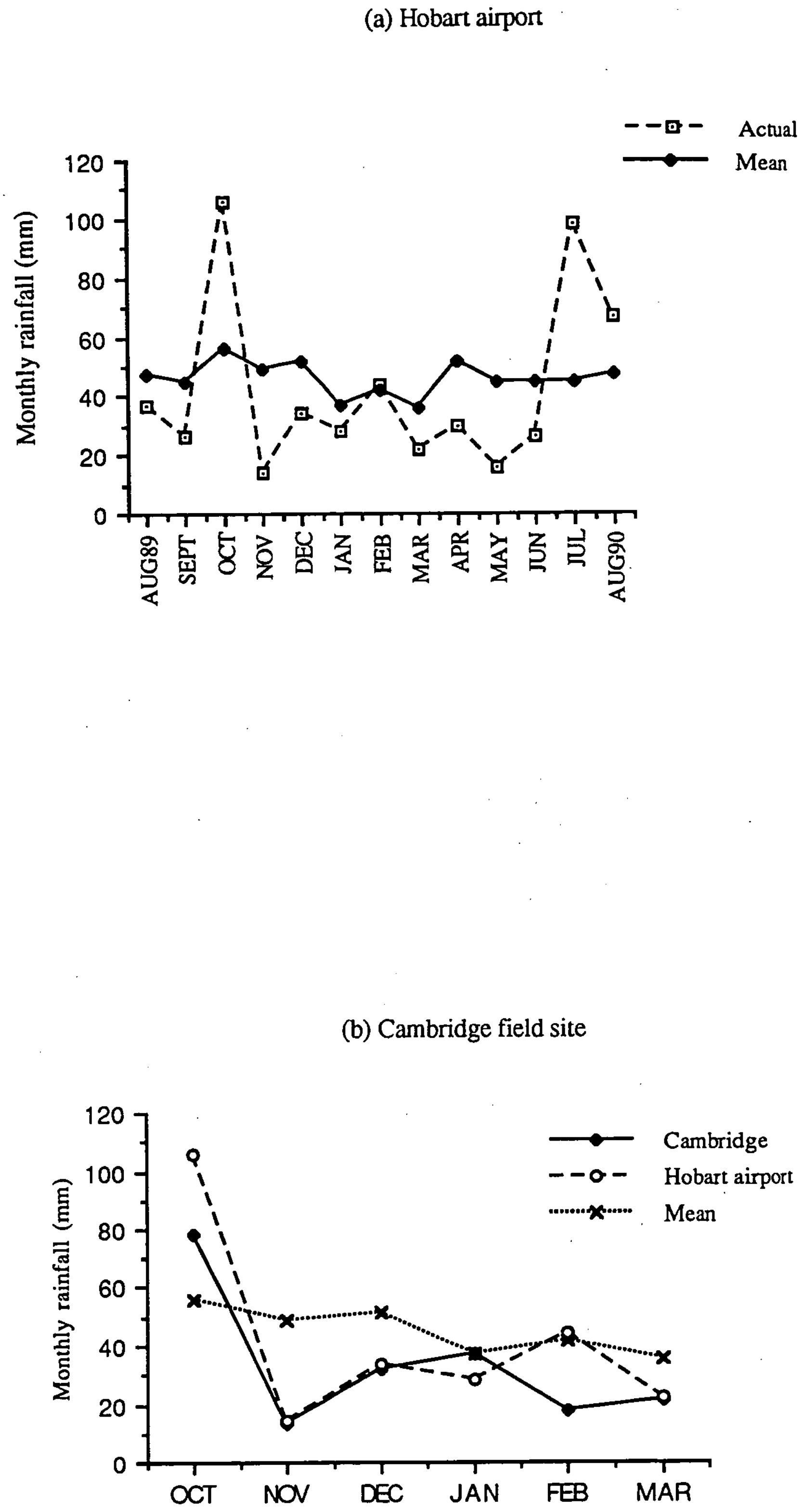
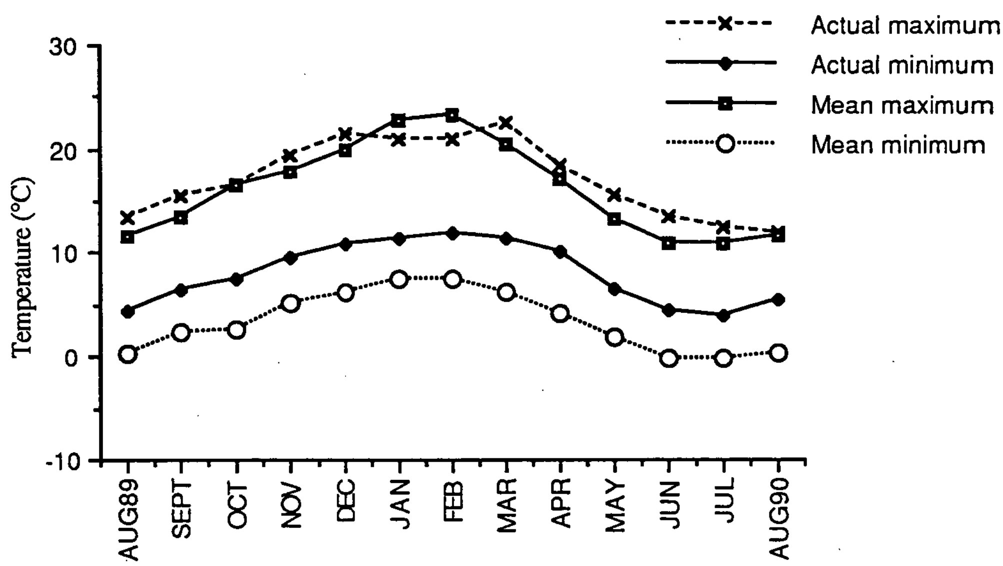


Figure 3.2. Mean monthly rainfall, as recorded at the Cambridge field site and at Hobart airport.

(a) Hobart airport



(b) Cambridge field site

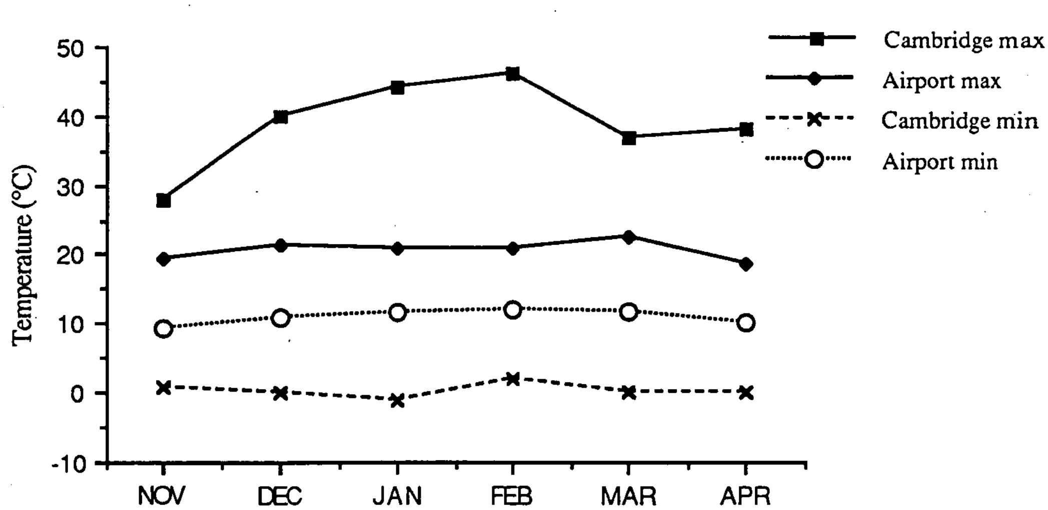


Figure 3.3. Maximum and minimum air temperatures recorded at the Cambridge field site and at Hobart airport. The measurements at the Cambridge site were taken at 10 cm above ground level, and those at the Hobart airport were taken under standard conditions.

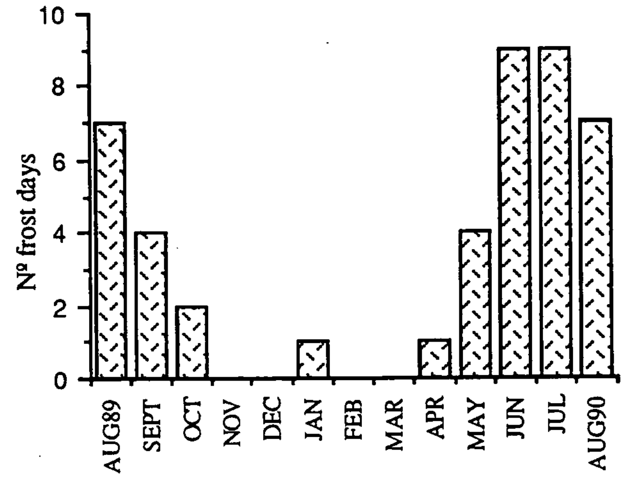


Figure 3.4. The number of frost days per month recorded at Hobart airport.

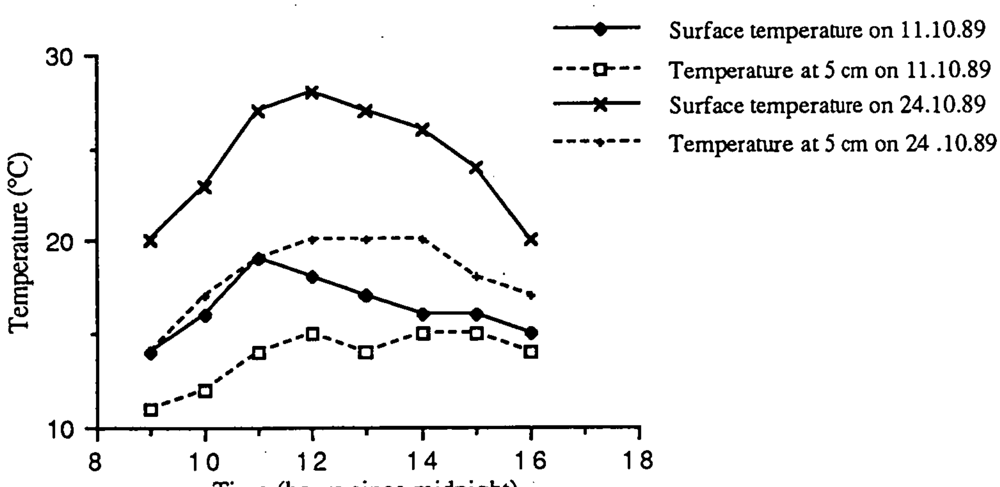


Figure 3.5. Changes in soil temperatures at the soil surface and at 5 cm depth, over the course of 8 hours, measured at two dates in October.

Table 3.4. ANOVA table of the effects of treatments on cumulative emergence in the Cambridge field trial.

Source of Variation	DF	MS	F	p
(a) Weed Control				
Irrigation	1	3.7664	15.64	0.0001
Block(irr)*	4	1.3830	5.71	0.0002
Weed control	2	7.0910	29.44	0.0001
Irrigate x weed control	2	0.1353	0.56	0.5713
Block x Weed control(irr)	8	0.5541	2.30	0.0232
Species	2	2.0162	8.37	0.0003
Irrigate x species	2	0.1560	0.65	0.5245
Weed control x species	4	0.1186	0.49	0.7412
Irr x weed cont x species	4	0.1681	0.70	0.5944
Block x weed cont x sp(irr)**	24	0.2043	0.85	0.6710
RESIDUAL	162	0.2408		
(b) No Weed Control±Fert				
Irrigation	1	0.2148	1.02	0.3152
Block(irr)	4	0.8591	4.07	0.0041
Fertilizer	1	0.0642	0.30	0.5821
Irrigate x fertilizer	1	0.4236	2.01	0.1594
Block x fertilizer(irr)	4	0.1769	0.84	0.5037
Species	2	0.8452	4.01	0.0210
Irrigate x species	2	0.2098	0.99	0.3732
Fertilizer x species	2	0.1048	0.50	0.6097
Irr x fertilizer x species	2	0.0610	0.29	0.7494
Block x fertilizer x sp(irr)	16	0.1016	0.48	0.9513
RESIDUAL	103	0.2110		
(c) Initial Weed Control±Fertilize				
Irrigation	1	10.1285	35.83	0.0001
Block(irr)	4	9.1719	32.44	0.0001
Fertilizer	1	0.1408	0.50	0.4800
Irrigate x fertilizer	1	0.0061	0.02	0.8829
Block x fertilizer(irr)	4	0.2339	0.51	0.8300
Species	2	3.0515	10.79	0.0001
Irrigate x species	2	0.1739	0.62	0.5409
Fertilizer x species	2	0.0253	0.09	0.1942
Irr x fertilizer x species	2	0.2532	0.90	0.4091
Block x fertilizer x sp(irr)	16	0.4100	1.45	0.1152
RESIDUAL	396	0.2827		
(d) Initial Weed Control±Mulch				
Irrigation	1	11.4718	46.31	0.0001
Block(irr)	4	10.6131	42.84	0.0001
Mulch	1	10.6637	43.05	0.0001
Irrigate x mulch	1	0.0007	0.00	0.9563
Block x mulch(irr)	4	0.0453	1.83	0.1222
Species	2	3.2551	13.14	0.0001
Irrigate x species	2	0.1833	0.74	0.4778
Mulch x species	2	0.6420	2.59	0.0761
Irr x mulch x species	2	0.1132	0.46	0.6335
Block x mulch x sp(irr)	16	0.5118	2.07	0.0091
RESIDUAL	396	0.2477		
(e) Long Term Weed Control±Mulch				
Irrigation	1	1.1189	5.08	0.0260
Block(irr)	4	1.2348	5.61	0.0004
Mulch	1	0.5296	2.41	0.1235
Block x mulch(irr)	2	0.1862	0.85	0.4315
Species	2	2.4343	11.06	0.0001
Irrigate x species	2	0.2787	1.27	0.2856
Mulch x species	2	0.1062	0.48	0.0182
Block x mulch x sp(irr)	12	0.3250	1.48	0.1424
RESIDUAL	117	0.2200		

* irr = irrigate
** sp = species

Irrigation

Irrigation significantly influenced seedling emergence and survival in weed control treatments ($P<0.0001$) (Table 3.1, 3.5, 3.7), but in most cases did not affect mean seedling height after 6 or 12 months (Table 3.12). A number of between-irrigation treatment differences were recorded. Emergence of *E. amygdalina* was greater with than without irrigation, irrespective of weed control treatment (Table 3.5). Irrigation also increased *E. pauciflora* emergence above that in unirrigated plots, except where long term weed control was applied. Conversely, irrigation did not affect the emergence of *E. ovata* except where long term weed control was applied, when an increase was recorded (Table 3.5, Figure 3.6). With only two exceptions, irrigation consistently increased the number of seedlings of each species surviving in the three weed control treatments, although the increases were small (Table 3.6, Figure 3.7).

Irrigation increased the emergence of *E. pauciflora* and *E. amygdalina*, and the survival of all species in plots with initial weed control and fertilizer, but there was no consistent trend in plots with no weed control and fertilizer (Tables 3.9, 3.10, Figures 3.9, 3.10). When irrigation was added to plots with initial weed control and mulch, emergence of all species, and survival of *E pauciflora* and *E. amygdalina* were also increased (Figure 3.12, 3.13).

In all cases, the difference in survival of seedlings in irrigated and unirrigated plots, while significant, was very small.

Table 3.5. Mean cumulative emergence (%) in weed control treatments in the Cambridge field experiment ($P<0.05$). Different letters indicate treatment differences. N = 12.

Treatment	Species emergence (%)		
	E pauciflora	*E ovata*	*E. amygdalina*
Initial weed control	2.14^{ef} (2.00-2.28)	2.94^{cd} (2.61-3.32)	2.93^{d} (2.75-3.12)
Long term weed cont	2.33^{e} (2.19-2.47)	2.18^{ef} (1.93-2.46)	3.07^{cd} (2.82-3.35)
No weed control	1.51^{g} (1.46-1.58)	1.55^{fg} (1.44-1.66)	1.72^{f} (1.61-1.84)
Initial + irrigation	3.09^{cd} (2.91-3.28)	3.50^{c} (3.19-3.84)	4.98^{a} (4.52-5.48)
Long term + irrigation	2.36^{e} (2.21-2.52)	3.37^{cd} (3.09-3.68)	4.13^{b} (3.93-4.33)
No weed control + irrigation	1.74^{f} (1.62-1.88)	1.82^{f} (1.65-2.01)	2.22^{e} (2.06-2.40)

Table 3.6. Survival of seedlings at Cambridge after 12 months, at different levels of weed control ($P<0.05$). Different lettersindicate treatment differences. N = 12.

Treatment	Mean survival (%)		
	E pauciflora	*E ovata*	*E. amygdalina*
Initial weed control	1.01^{f} (1.00-1.02)	1.11^{d} (1.07-1.16)	1.06^{de} (1.05-1.08)
Long term weed cont	1.10^{d} (1.09-1.12)	1.24^{c} (1.17-1.31)	1.24^{c} (1.19-1.29)
No weed control	1.01^{f} (1.01-1.02)	0^{g}	0^{g}
Initial + irrigation	1.04^{ef} (1.02-1.05)	1.23^{c} (1.18-1.32)	1.24^{c} (1.19-1.298
Long term + irrigation	1.17^{c} (1.13-1.21)	2.16^{a} (1.97-2.36)	1.80^{b} (1.65-1.95)
No weed control + irrigation	1.04^{e} (1.02-1.06)	0^{g}	1.01^{f} (1.01-1.02)

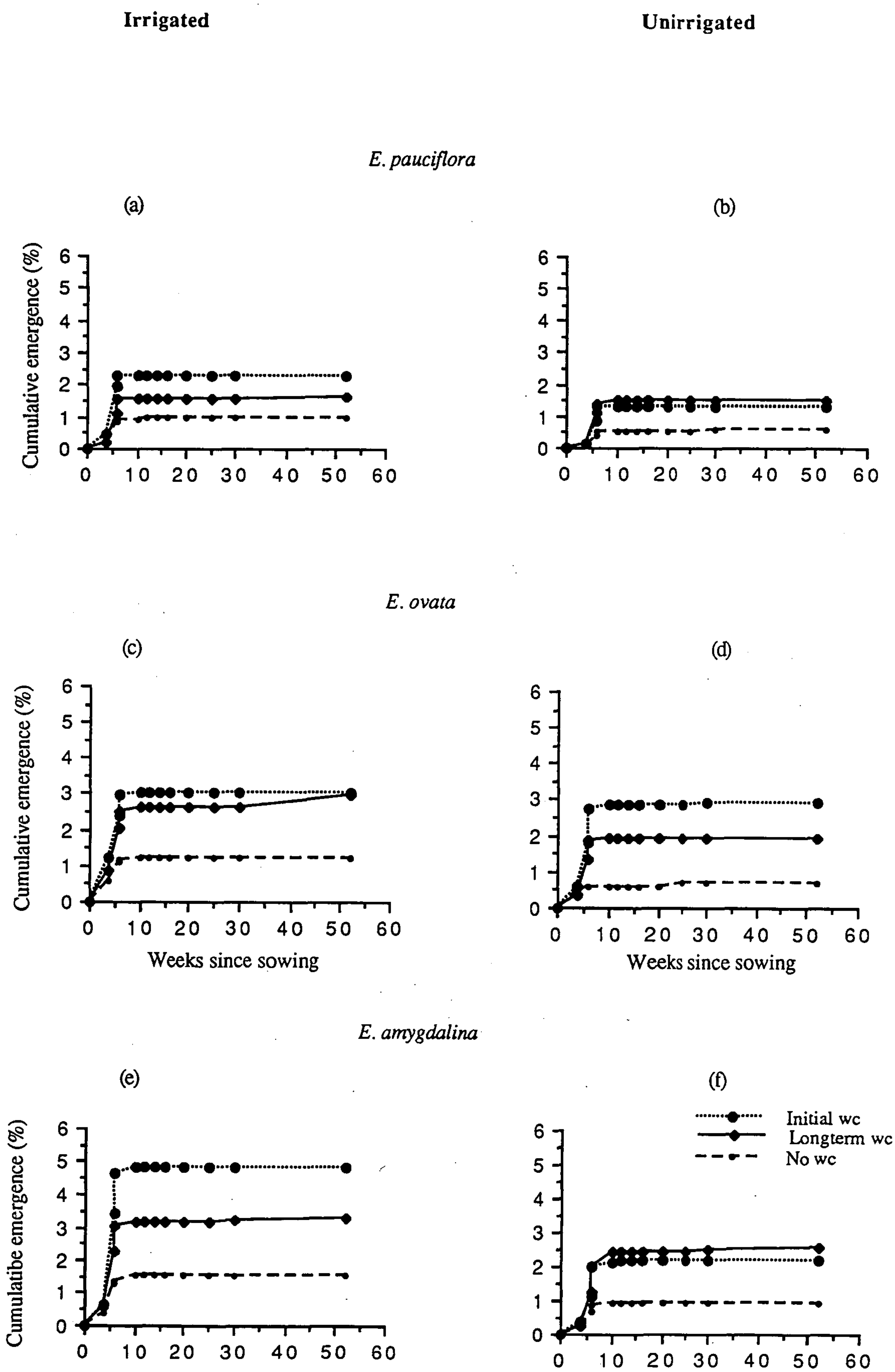


Figure 3.6. Effect of weed control and irrigation on emergence in the Cambridge field experiment.

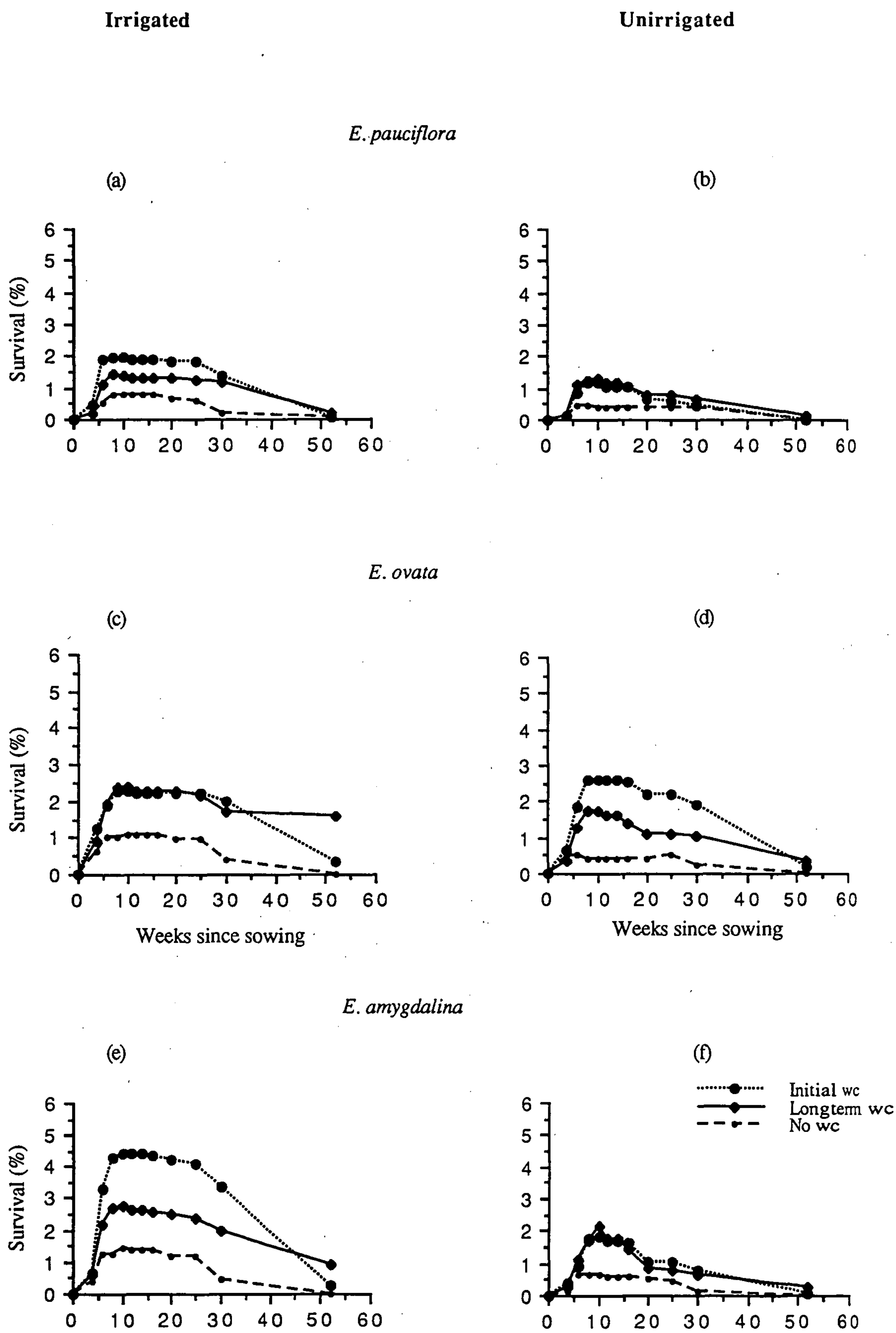


Figure 3.7. Effect of weed control and irrigation on survival in the Cambridge field experiment.

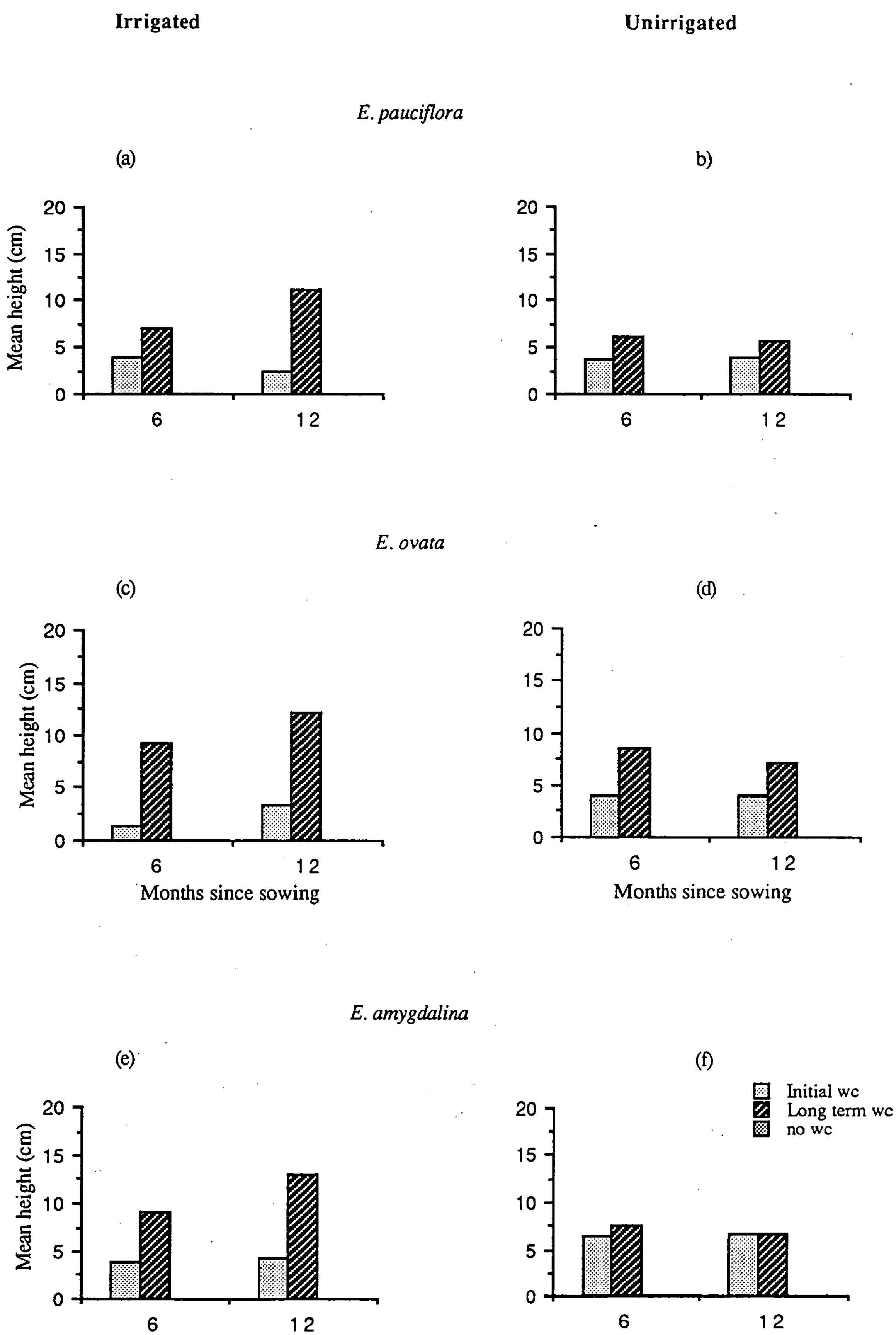


Figure 3.8. Effect of weed control and irrigation on seedling height after 6 and 12 months in the Cambridge field experiment (there were no seedlings in treatments with no weed control).

Weed Control

Seedling emergence (P<0.0001), survival (P<0.0001), and height after 6 (P<0.01) and 12 (P<0.0001) months were all significantly influenced by the level of weed control (Tables 3.4, 3.7, 3.12, Figures 3.6, 3.7, 3.8). In all cases emergence was increased by some form of weed control. In irrigated plots there was greater emergence of *E. pauciflora* and *E. amygdalina* with initial weed control than with long term control (Table 3.5). In unirrigated plots only *E. ovata* emergence was greater with initial than with long term weed control. The rate (speed) of emergence was generally unaffected by weed control treatment, although in some instances (eg Figure 3.6 b, c, e) the rate was slightly slower when weed control was not applied. In all cases, long term weed control resulted in a greater number of seedlings surviving after 12 months (Table 3.6, Figure 3.7). Survival in plots with long term weed control was further increased by the addition of irrigation.

After both 6 and 12 months, the mean height of the tallest seedling of each species was greater in plots with long term than with initial weed control when irrigation was applied. Without irrigation, this was also true for all species after 12 months (Table 3.8, Figure 3.8). The number of seedlings surviving in plots without weed control was too small for analysis of height differences. While, in the absence of irrigation, long term weed control increased mean seedling height above that recorded in plots with initial weed control, only the combination of long term weed control and irrigation resulted in a positive change in *E. pauciflora* or *E. amygdalina* height between 6 and 12 months. No such change was recorded for *E. ovata* in this treatment, although it was apparent when seedlings were grown with initial weed control and irrigation. Despite the termination of irrigation 7 months after sowing, a mean increment of 4.19 cm was recorded for *E. pauciflora*, 2.81 cm for *E. ovata*, and 3.87 cm for *E. amygdalina* in plots which had long term weed control plus initial irrigation.

The mean height after 12 months of *E. pauciflora* seedlings growing in plots with initial weed control and irrigation was significantly less than the height of those growing without irrigation (Table 3.8). Similarly, the height of *E. ovata* was less after 6 months with the combination of initial weed control and irrigation than in plots with only initial weed control. While the difference was not significant, the mean height of *E. amygdalina* seedlings after 6 months in plots with initial weed control and irrigation was approximately 60% of that of seedlings in plots with initial weed control and no irrigation. The combination of initial weed control and irrigation resulted in a greater density of weeds than did initial weed control without irrigation (observation only).

Table 3.7. ANOVA table of percentage seedling survival for the treatments in the Cambridge field trial.

Source of Variation	DF	MS	F	p
(a) Weed Control				
Irrigation	1	1.1615	24.00	0.0001
Block(irr)	4	0.1143	2.36	0.0553
Weed control	2	2.0709	42.80	0.0001
Irrigate x weed control	2	0.4677	9.67	0.0001
Block x weed control(irr)	8	0.0682	1.41	0.1961
Species	2	0.5046	10.43	0.0001
Irrigate x species	2	0.1691	3.50	0.0326
Weed control x species	4	0.2493	5.15	0.0006
Irr x weed cont x species	4	0.1176	2.43	0.0496
Block x weed cont x sp(irr)	24	0.1202	2.49	0.0004
RESIDUAL	162	0.0483		
(b) No Weed Control±Fert				
Irrigation	1	0.0255	3.59	0.0609
Block(irr)	4	0.0300	4.23	0.0032
Fertilizer	1	0.0016	0.23	0.6325
Irrigate x fertilizer	1	0.0044	0.63	0.4309
Block x fertilizer(irr)	4	0.0030	0.43	0.7884
Species	2	0.0071	1.00	0.3714
Irrigate x species	2	0.0082	1.16	0.3180
Fertilizer x species	2	0.0235	3.32	0.0400
Irr x fertilizer x species	2	0.0187	2.64	0.0760
Block x fertilizer x sp(irr)	16	0.0144	2.03	0.0172
RESIDUAL	103	0.0071		
(c) Initial Weed Control±Fert				
Irrigation	1	1.1008	24.54	0.0001
Block(irr)	4	0.1015	2.26	0.0617
Fertilizer	1	0.0081	0.28	0.6710
Irrigate x fertilizer	1	0.0067	0.15	0.6974
Block x fertilizer(irr)	4	0.0689	1.54	0.1908
Species	2	0.2042	4.55	0.0111
Irrigate x species	2	0.0534	1.19	0.3052
Fertilizer x species	2	0.0199	0.44	0.6418
Irr x fertilizer x species	2	0.0062	0.14	0.8708
Block x fertilizer x sp(irr)	16	0.0318	0.71	0.7833
RESIDUAL	396	0.0448		
(d) Initial Weed Control±Mulch				
Irrigation	1	1.2633	28.17	0.0001
Block(irr)	4	0.1246	2.78	0.0267
Mulch	1	0.0867	1.93	0.1652
Irrigate x mulch	1	0.0097	0.22	0.6421
Block x mulch(irr)	4	0.0150	0.34	0.8541
Species	2	0.2293	5.11	0.0064
Irrigate x species	2	0.0684	1.53	0.2186
Mulch x species	2	0.0402	0.90	0.4087
Irr x mulch x species	2	0.0298	0.67	0.5146
Block x mulch x sp(irr)	16	0.0352	0.79	0.7013
RESIDUAL	396	0.0448		
(e) Long Term Weed Control±Mulch				
Irrigation	1	1.9204	24.99	0.0001
Block(irr)	4	0.1383	1.80	0.1334
Mulch	1	0.2455	3.20	0.0764
Block x mulch(irr)	2	0.1442	1.88	0.1575
Species	2	1.0627	13.83	0.0001
Irrigate x species	2	0.3762	4.90	0.0091
Mulch x species	2	0.0490	0.64	0.5301
Block x mulch x sp(irr)	12	0.2736	3.56	0.0002
RESIDUAL	117	0.0768		

Table 3.8. Mean height of the tallest seedlings at Cambridge with different levels of weed control, both 6 and 12 months after sowing (P<0.05). Different letters in the same column indicate treatment differences.

Treatment	Mean height (cm) after 6 months			Mean height (cm) after 12 months		
	E pauciflora	*E ovata*	*E.amygdalina*	*E pauciflora*	*E ovata*	*E. amygdalina*
Initial weed control	3.77^{bc} (3.35-4.25)	3.87^{c} (3.61-4.31)	6.34^{bc} (4.25-7.14)	3.87^{c} (3.44-4.36)	3.87^{c} (3.44-4.36)	3.63^{c} (3.03-4.36)
Long term weed cont	6.10^{b} (5.66-6.57)	8.43^{a} (7.72-9.20)	7.47^{ab} (6.23-8.94)	5.76^{b} (5.22-6.35)	7.07^{b} (6.20-8.06)	6.71^{b} (5.49-8.21)
No weed control	-	-	-	-	-	-
Initial + irrigation	3.85^{c} (2.13-3.62)	1.41^{d} (1.22-1.63)	3.85^{bc} (2.93-5.06)	2.45^{d} (2.30-2.69)	3.31^{c} (2.73-4.01)	4.31^{bc} (3.40-5.46)
Long term + irrigation	6.96^{ab} (5.44-8.92)	9.25^{a} (7.50-11.42)	9.10^{a} (7.55-11.21)	11.15^{a} (9.34-13.65)	12.07^{a} (10.67-13.65)	13.06^{a} (11.28-15.12)
No weed control + irrigation	-	-	-	-	-	-

Fertilizer Addition

When fertilizer was added to plots with initial or no weed control, there was no consistent effect on emergence in any treatment (Table 3.9, Figure 3.9). Only in two instances was there a significant difference between fertilized and unfertilized treatments. Emergence of *E. pauciflora* was less in plots with irrigation, fertilizer and no weed control than in plots with the same treatment but no fertilizer. Conversely, *E. amygdalina* emergence was greater in plots with no weed control, irrigation and fertilizer than in plots with the same treatment but no fertilizer.

In plots with initial weed control, fertilizer addition had no effect on seedling survival, except that the combination of irrigation and fertilizer increased the number of seedlings of *E. amygdalina* surviving. In plots without weed control, fertilizer addition decreased the survival of *E. pauciflora* (both with and without irrigation), and of *E. amygdalina* when irrigation was applied, although the survival of *E. ovata* seedlings in irrigated plots was greater when fertilizer was applied (Table 3.10, Figure 3.10).

The effect of fertilizer addition on mean height of seedlings with initial weed control was also variable (Table 3.11, Figure 3.11). After 6 months there were some differences between fertilized and unfertilized treatments, such as an increase in the mean height of *E. ovata* and *E. amygdalina* when fertilizer was added to plots with initial weed control and irrigation. There was also an increase in *E. pauciflora* height when fertilizer was combined with initial weed control and no irrigation, but in this same treatment, *E. amygdalina* seedling height was decreased with fertilizer addition. After 12 months, the addition of fertilizer at the time of sowing was no longer influencing mean seedling height of *E. pauciflora* or *E. amygdalina*, although the height of *E. ovata* grown without irrigation was significantly greater with than without fertilizer addition (Table 3.11).

Table 3.9. Mean cumulative emergence at Cambridge in treatments where fertilizer was added (P<0.05). Different letters within weed control treatments indicate treatment differences. N = 12 (no weed control); N = ≥ 24 (initial weed control).

Treatment	Species emergence (%)		
	E pauciflora	*E ovata*	*E. amygdalina*
(a) Initial Weed Control			
Control	1.97^{d} (1.89-2.06)	2.40^{c} (2.22-2.6)	2.61^{c} (2.48-2.75)
Fertilizer	2.07^{d} (1.96-2.19	2.07^{bc} (1.90-2.24)	2.54^{c} (2.40-2.69)
Irrigation	2.76^{bc} (2.65-2.88)	2.91^{bc} (2.70-3.13)	3.96^{a} (3.72-4.21)
Irrigation+fertilizer	2.58^{c} (2.48-2.69)	3.05^{b} (2.818-3.30)	3.68^{a} (3.48-3.89)
(b) No Weed Control			
Control	1.52^{c} (1.44-1.59)	1.55^{bc} (1.42-1.69)	1.73^{bc} (1.59-1.88)
Fertilizer	1.52^{c} (1.43-1.63)	1.01^{abcd} (0.63-2.04)	1.79^{bc} (1.59-1.88)
Irrigation	1.75^{bc} (1.59-1.92)	1.82^{ab} (1.61-2.06)	1.79^{b} (1.64-1.95)
Irrigation+fertilizer	1.29^{d} (1.23-1.35)	1.60^{bc} (1.46-1.76)	2.19^{a} (1.99-2.41)

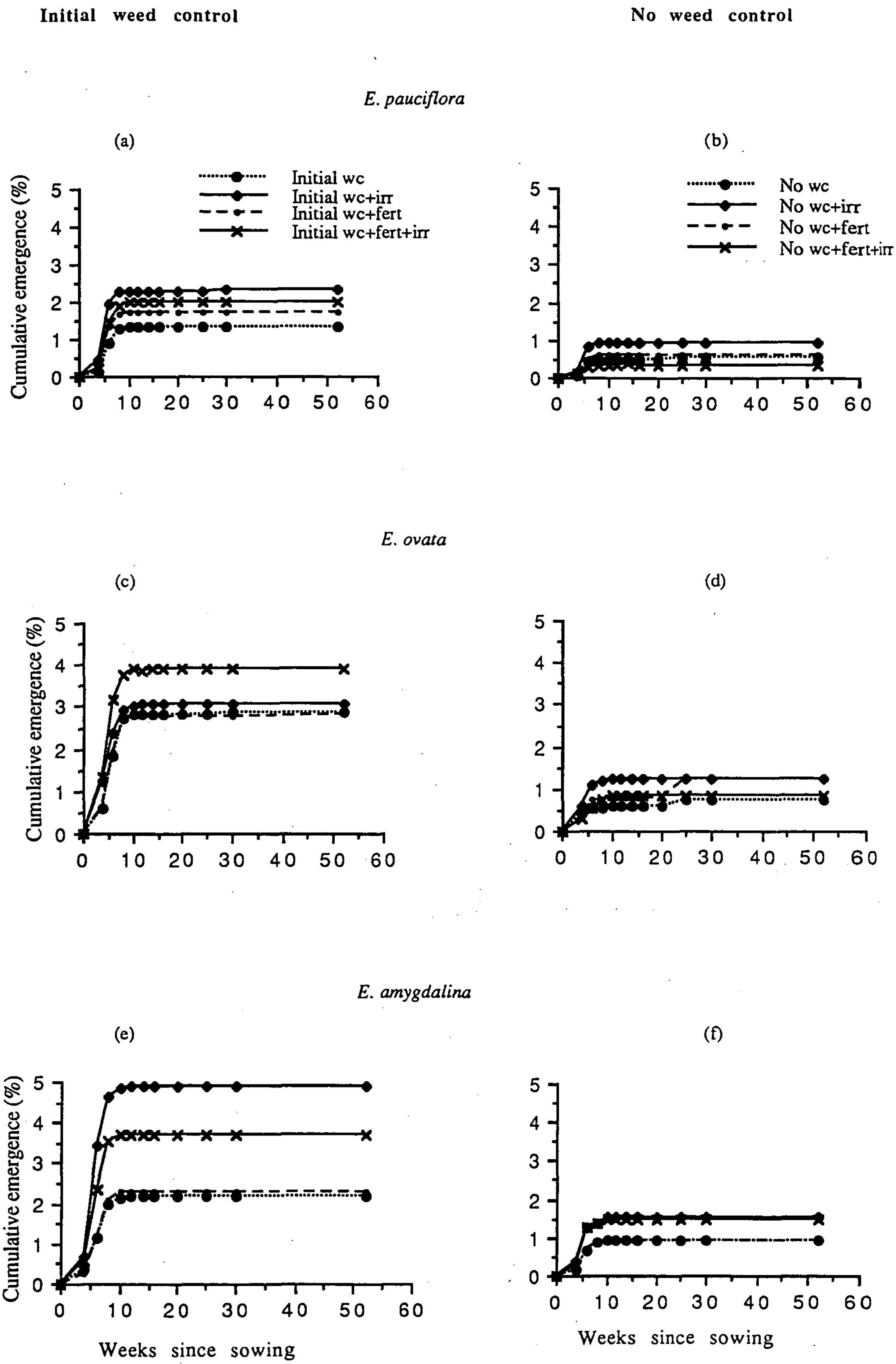


Figure 3.9. Effect of fertilizer addition on emergence of seedlings in the Cambridge field experiment.

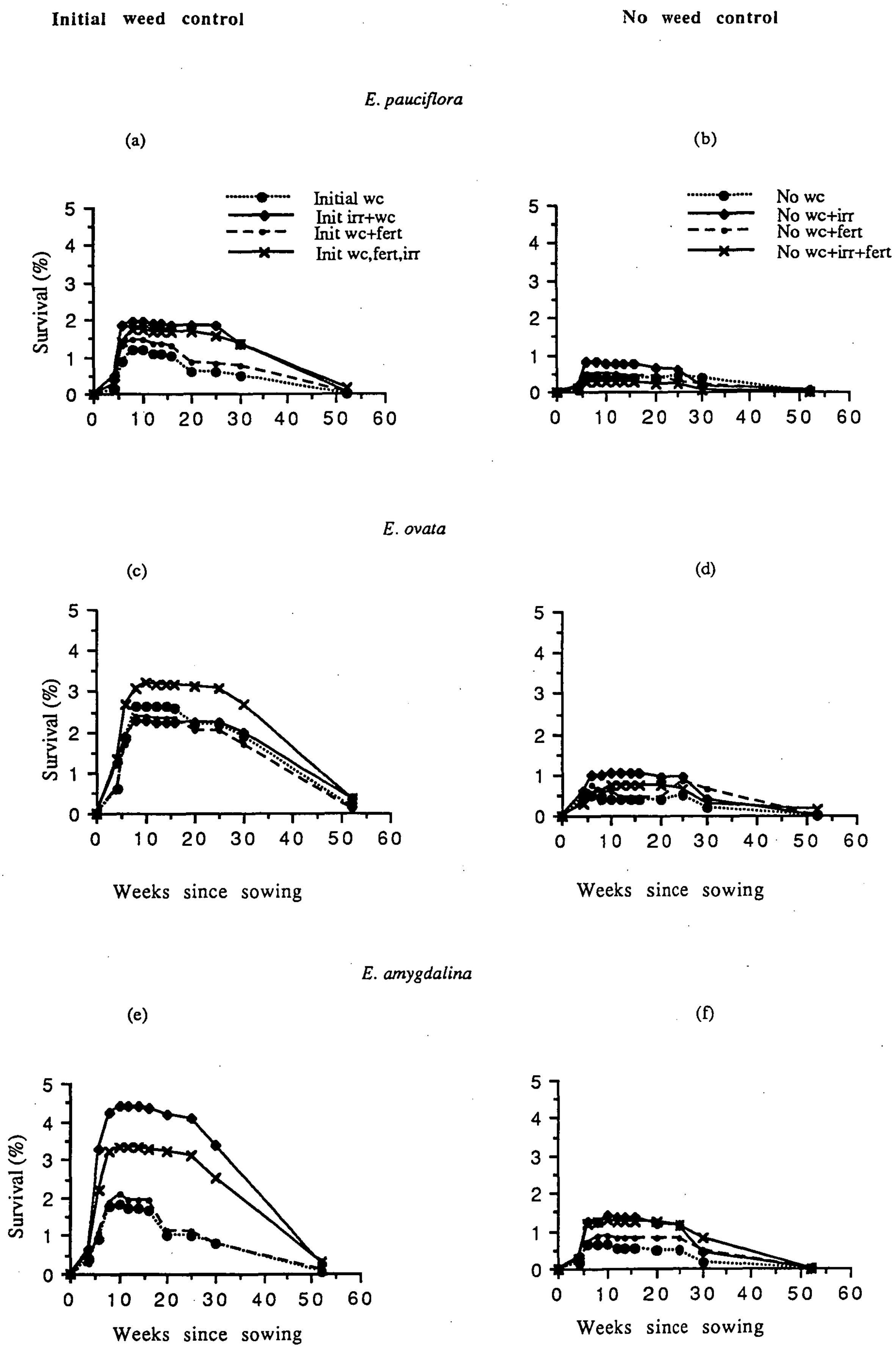


Figure 3.10. Effect of fertilizer addition on survival of seedlings in the Cambridge field experiment.

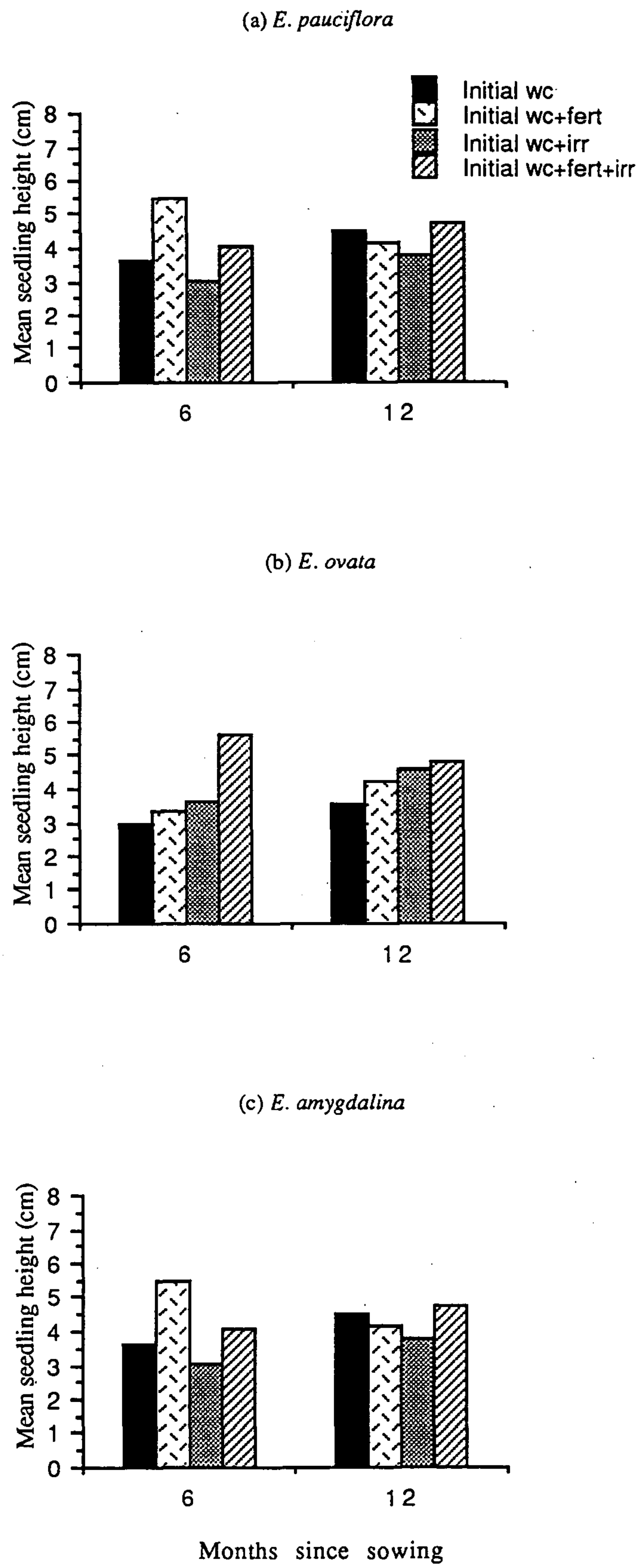


Figure 3.11. Effect of fertilizer addition on the mean height of seedlings at Cambridge in plots with initial weed control, 6 and 12 months after sowing.

Table 3.10. Seedling survival (%) at Cambridge after 12 months, with and without fertilizer addition (P<0.05). Different letters within the same weed control treatment indicate treatment differences. N = 12.

Treatment	Species survival (%)		
	E pauciflora	*E ovata*	*E. amygdalina*
(a) Initial Weed Control			
Control	1.02^{d} (1.01-1.03)	1.08^{c} (1.06-1.10)	1.05^{c} (1.02-1.07)
Fertilizer	1.02^{d} (1.01-1.03)	1.07^{c} (1.04-1.09)	1.06^{c} (1.05-1.07)
Irrigation	1.09^{c} (1.07-1.10)	1.19^{b} (1.16-1.23)	1.20^{b} (1.17-1.23)
Irrigation+fertilizer	1.11^{bc} (1.09-1.13)	1.17^{b} (1.13-1.20)	1.33^{a} (1.29-1.37)
(b) No Weed Control			
Control	1.01^{b} (1.00-1.02)	0^{c}	0^{c}
Fertilizer	0^{c}	0^{c}	0^{c}
Irrigation	1.04^{ab} (1.01-1.07)	0^{c}	1.02^{b} (1.00-1.03)
Irrigation+fertilizer	0^{c}	1.12^{a} (1.06-1.18)	0^{c}

Table 3.11. Mean height (cm) of seedlings at Cambridge in fertilized plots, 6 and 12 months after sowing ($P<0.05$). Different letters at 6 or 12 months indicate treatment differences.

Treatment	Mean height (cm) after 6 months			Mean height (cm) after 12 months		
	E pauciflora	*E ovata*	*E.amygdalina*	*E pauciflora*	*E ovata*	*E. amygdalina*
(a) Initial Weed Control						
Control	3.67^{ef} (3.45-3.89)	2.94^{g} (2.55-3.40)	7.32^{a} (6.71-7.98)	4.51^{bc} (4.30-4.73)	3.56^{d} (3.35-3.78)	4.87^{ab} (4.41-5.36)
Fertilizer	5.45^{bc} (4.82-6.17)	3.33^{efg} (3.03-3.752)	4.16^{de} (3.65-4.73)	4.13^{bcd} (3.58-4.75)	4.24^{bc} (3.90-4.61)	4.77^{abc} (4.21-5.41)
Irrigation	3.03^{fg} (2.58-3.54)	3.59^{efg} (2.99-4.31)	4.11^{cde}f (3.44-4.90)	3.80^{cd} (2.29-4.26)	4.61^{ab}c (3.99-5.32)	5.01^{ab} (4.38-5.73)
Irrigation+fertilizer	4.08^{cdef} (3.44-4.85)	5.61^{bcd} (4.73-6.65	5.94^{a}b (5.14-6.86)	4.72^{abc} (4.14-5.35)	4.80^{a}b (4.07-5.66)	5.64^{a} (4.95-6.37)

Table 3.12. ANOVA table for the height of seedlings in various treatments in the Cambridge field trial, 6 and 12 months from sowing.

	6 Months After Sowing				12 Months After Sowing			
Source of Variation	DF	MS	F	p	DF	MS	F	p
(a) Weed Control								
Irrigation	1	0.4866	0.85	0.3609	1	1.1384	3.60	0.0654
Block(irr)	4	0.2046	0.36	0.8370	4	0.2598	0.82	0.5194
Weed control	2	2.9487	5.16	0.0095	2	4.1096	13.00	0.0001
Irr x weed cont	2	0.6330	1.11	0.3389	1	1.8201	5.76	0.0214
Block x weed cont(irr)	4	0.6808	1.19	0.3273	3	0.0525	0.17	0.9185
Species	2	0.3304	0.58	0.5650	2	0.0862	0.27	0.7627
Irr x species	2	0.0361	0.06	0.9389	2	0.0633	0.20	0.8192
Weed cont x species	4	0.1077	0.19	0.9432	3	0.0617	0.20	0.8988
Irr x weed cont x sp	2	0.0662	0.12	0.8908	2	0.1046	0.33	0.7202
Block x wc x sp(irr)	9	0.1570	0.27	0.9784	9	0.0848	0.27	0.9795
RESIDUAL	46	0.5715			38	0.3161		
(b) Long term Weed Control ± Mulch								
Irrigation	1	0.6816	1.77	0.1881	1	4.4814	13.37	0.0005
Block(irr)	4	0.5500	1.43	0.2347	4	0.2596	0.77	0.5459
Mulch	1	0.5376	1.39	0.2418	1	0.1371	0.41	0.5248
Irr x mulch	1	0.0855	0.22	0.6392	1	0.8726	2.60	0.1119
Block x mulch(irr)	4	0.4159	1.08	0.3739	4	0.5353	1.60	0.1868
Species	2	0.5571	1.45	0.2429	2	0.6662	1.99	0.1959
Irr x species	2	0.0623	0.16	0.8509	2	0.2171	0.65	0.5268
Mulch x species	2	0.0068	0.02	0.9823	2	0.3309	0.99	0.3786
Irr x mulch x sp	2	0.0463	0.12	0.8868	2	0.2425	0.72	0.4892
Block x mulch x sp(irr)	14	0.2402	0.62	0.8360	13	0.1996	0.60	0.8481
RESIDUAL	66	0.3854			60	0.3351		
(d) Initial Weed Control±Fertilizer								
Irrigation	1	0.0058	0.01	0.9246	1	0.2500	0.65	0.4237
Block(irr)	4	0.6446	1.00	0.4122	4	0.6066	1.57	0.1898
Fertilizer	1	0.2487	0.38	0.5362	1	0.0063	0.02	0.8980
Irr x fertilizer	1	1.1457	1.77	0.1856	1	0.0027	0.01	0.9326
Block x fertilizer(irr)	4	0.5258	0.81	0.5190	4	0.1963	0.51	0.7307
Species	2	0.3406	0.53	0.5918	2	0.2477	0.64	0.5297
Irr x species	2	1.4317	2.22	0.1140	2	0.1458	0.38	0.6871
Fertilizer x species	2	0.4023	0.62	0.5385	2	0.0429	0.11	0.8951
Irr x fertilizer x sp	2	0.4561	0.71	0.4960	2	0.2942	0.76	0.4706
Block x fert x sp(irr)	13	0.4242	0.66	0.8007	12	0.3451	0.89	0.5585
RESIDUAL	109	0.6462			92	0.3872		
(e) Initial Weed Control ± Mulch								
Irrigation	1	0.0016	0.00	0.9571	1	0.6348	1.81	0.1816
Block(irr)	4	0.6556	1.18	0.3247	4	0.1882	0.54	0.7086
Mulch	1	6.9219	12.43	0.0006	1	1.3149	3.75	0.0558
Irr x mulch	1	0.1737	0.31	0.5775	1	1.2122	3.46	0.0660
Block x mulch(irr)	4	1.7889	3.21	0.0155	4	0.3950	1.13	0.3484
Species	2	0.0200	0.04	0.9646	2	0.2508	0.72	0.4913
Irr x species	2	0.8449	1.52	0.2238	2	0.1046	0.30	0.7426
Mulch x species	2	0.1995	0.36	0.6996	2	0.0216	0.06	0.9402
Irr x mulch x sp	2	0.9711	1.74	0.1796	2	0.0385	1.10	0.3373
Block x mulch x sp(irr)	11	0.2179	0.39	0.9570	12	0.1017	0.29	0.9896
RESIDUAL	111	0.5569			92	0.3503		

Mulch

When mulch was applied to plots with initial weed control, it significantly ($P<0.0001$) reduced the mean cumulative emergence of all species, both with and without irrigation (Tables 3.1, 3.13). When it was applied to plots with long term weed control, however, a significant increase in *E. amygdalina* emergence was recorded (Figure 3.12).

After 6 months, the addition of mulch to plots with initial weed control resulted in an increase in the mean height of the tallest *E. amygdalina* (with or without irrigation) and *E. pauciflora* (with irrigation) seedlings, but decreased the height of *E. ovata* seedlings when irrigation was not applied (Table 3.15). The combination of irrigation and mulch increased the height of all species above that recorded in plots with irrigation only (Table 3.15). After 12 months, this height increase was restricted, in *E. pauciflora* and *E. ovata*, to plots with rather than without irrigation (Table 3.15). Conversely, *E. amygdalina* seedlings in plots without irrigation demonstrated a significant height increase with mulch addition while in plots with irrigation there was no difference between treatments.

In plots with long term weed control, mulch had no effect on seedling height after 6 months, although the combination of irrigation and mulch increased *E. pauciflora* height. After 12 months, mulch had no effect on the height of any species in unirrigated plots. The combination of irrigation and mulch significantly decreased the mean height of *E. pauciflora* and *E. ovata* seedlings after 12 months.

In most cases, the presence of mulch did not result in a significant height increase between 6 and 12 months, although such an increase was recorded for *E. pauciflora* growing with initial weed control, irrigation and mulch, and for *E. ovata* grown with initial weed control and mulch (Figure 3.14, Table 3.15). A significant decrease in height between 6 and 12 months was measured in *E. amygdalina* when it was grown with initial weed control and mulch, and for *E. pauciflora* when it was grown with long term weed control, irrigation and mulch (Figure 3.14, Table 3.15).

Table 3.13. The effect on emergence of adding mulch to Cambridge plots with long term and initial weed control (P<0.05). Different letters within weed control treatments indicate treatment differences. N = 36 (initial weed control); N = 12 (long term weed control).

Treatment	Species emergence(%)		
	E pauciflora	*E ovata*	*E. amygdalina*
(a) Initial Weed Control			
Control	2.31^{e} (2.21-2.42)	2.80^{de} (2.58-3.03)	2.83^{d} (2.68-2.98)
Mulch	1.79^{f} (1.70-1.89)	1.68^{f} (1.56-1.80)	2.32^{e} (2.19-2.45)
Irrigation	2.91^{cd} (2.81-3.12)	3.69^{b} (3.44-3.97)	4.44^{a} (4.20-4.69)
Irrigation+mulch	2.39^{e} (2.28-2.50)	2.43^{e} (2.25-2.61)	3.21^{c} (3.04-3.40)
(b) Long Term Weed Control			
Control	2.33^{c} (2.16-2.50)	2.18^{c} (1.89-2.51)	3.07^{b} (2.77-3.40)
Mulch	2.36^{c} (2.27-2.46)	2.67^{bc} (2.33-3.06)	3.84^{a} (3.58-4.13)

* figures showing the effect of irrigation and mulch on emergence are unavailable.

Table 3.14. Mean survival of emergents at Cambridge after 12 months, with and without mulch (P<0.05). Different letters in weed control treatments indicate treatment differences. N = 36 (initial weed control), N = 12 (long term weed control).

Treatment	Species survival (%)		
	E pauciflora	*E ovata*	*E. amygdalina*
(a) Initial Weed Control			
Control	1.02^{c} (1.01-1.03)	1.08^{b} (1.06-1.10)	1.08^{b} (1.06-1.08)
Mulch	1.02^{c} (1.01-1.02)	1.06^{bc} (1.03-1.08)	1.04^{c} (1.03-1.05)
Irrigation	1.04^{c} (1.08-1.118	1.23^{a} (1.19-1.28)	1.25^{a} (1.22-1.28)
Irrigation+mulch	1.10^{b} (1.08-1.12)	1.11^{b} (1.08-1.14)	1.23^{a} (1.20-1.273
(b) Long Term Weed Control*			
Control	1.10^{c} (1.08-1.12)	1.24^{b} (1.16-1.23)	1.24^{b} (1.18-1.30)
Mulch	1.29^{b} (1.18-1.27)	1.22^{b} (1.20-1.34)	1.48^{a} (1.40-1.56)

* figures showing the effect of irrigation and mulch on survival are unavailable.

Table 3.15. Mean seedling height at Cambridge after 6 and 12 months for treatments involving mulch addition. Different letters at 6 or 12 months indicate treatment differences ($P<0.05$).

Treatment	Mean height (cm) after 6 months			Mean height (cm) after 12 months		
	E pauciflora	*E ovata*	*E.amygdalina*	*E pauciflora*	*E ovata*	*E. amygdalina*
(a) Initial Weed Control						
Control	3.89^{cde}	4.02^{cd}	4.41^{d}	4.17^{cd}	4.05^{cd}	4.32^{cd}
	(3.61-4.19)	(3.82-4.23)	(2.99-3.82)	(3.53-4.93)	(3.76-4.36)	(3.73-5.01)
Mulch	5.41^{c}	2.51^{e}	6.89^{b}	4.36^{bc}	3.78^{d}	5.45^{b}
	(4.79-6.16)	(2.16-2.91)	(6.36-7.45)	(4.19-5.95)	(3.48-4.11)	(5.18-5.74)
Irrigation	3.09^{e}	3.21^{de}	4.22^{cd}	3.28^{de}	2.89^{e}	4.84^{bc}
	(2.58-3.70)	(2.66-3.87)	(3.56-5.00)	(2.94-3.66)	(2.49-3.36)	(4.18-5.62)
Irrigation+mulch	4.62^{c}	8.37^{a}	7.04^{ab}	6.31^{b}	7.70^{a}	6.29^{b}
	(4.02-5.31)	(7.80-8.99)	(6.25-7.92)	(5.72-6.96)	(7.37-8.05)	(5.69-6.95)
(b) Long Term Weed Control						
Control	6.10^{c}	8.43^{b}	7.47^{bc}	5.76^{c}	7.09^{c}	6.72^{c}
	(5.73-6.49)	(7.88-9.07)	(6.42-8.70)	(5.33-6.22)	(6.38-7.84)	(5.73-7.87)
Mulch	6.19^{c}	8.71^{b}	8.06^{b}	6.09^{c}	8.19^{bc}	6.94^{c}
	(4.41-7.09)	(8.09-9.37)	(7.30-8.40)	(5.40-6.86)	(6.50-10.31)	(6.13-7.87)
Irrigation	6.97^{bc}	9.26^{ab}	9.19^{ab}	11.16^{a}	12.07^{a}	13.06^{a}
	(5.67-8.56)	(7.78-11.02)	(7.79-10.84)	(9.70-12.84)	(10.96-13.30)	(11.64-14.66)
Irrigation+Mulch	10.70^{a}	9.26^{ab}	12.11^{a}	$7.68^{b}c$	9.18^{b}	12.73^{a}
	(9.61-11.93)	(7.68-11.16)	(10.18-14.34)	(6.22-9.47)	(7.85-10.74)	(10.69-15.14)

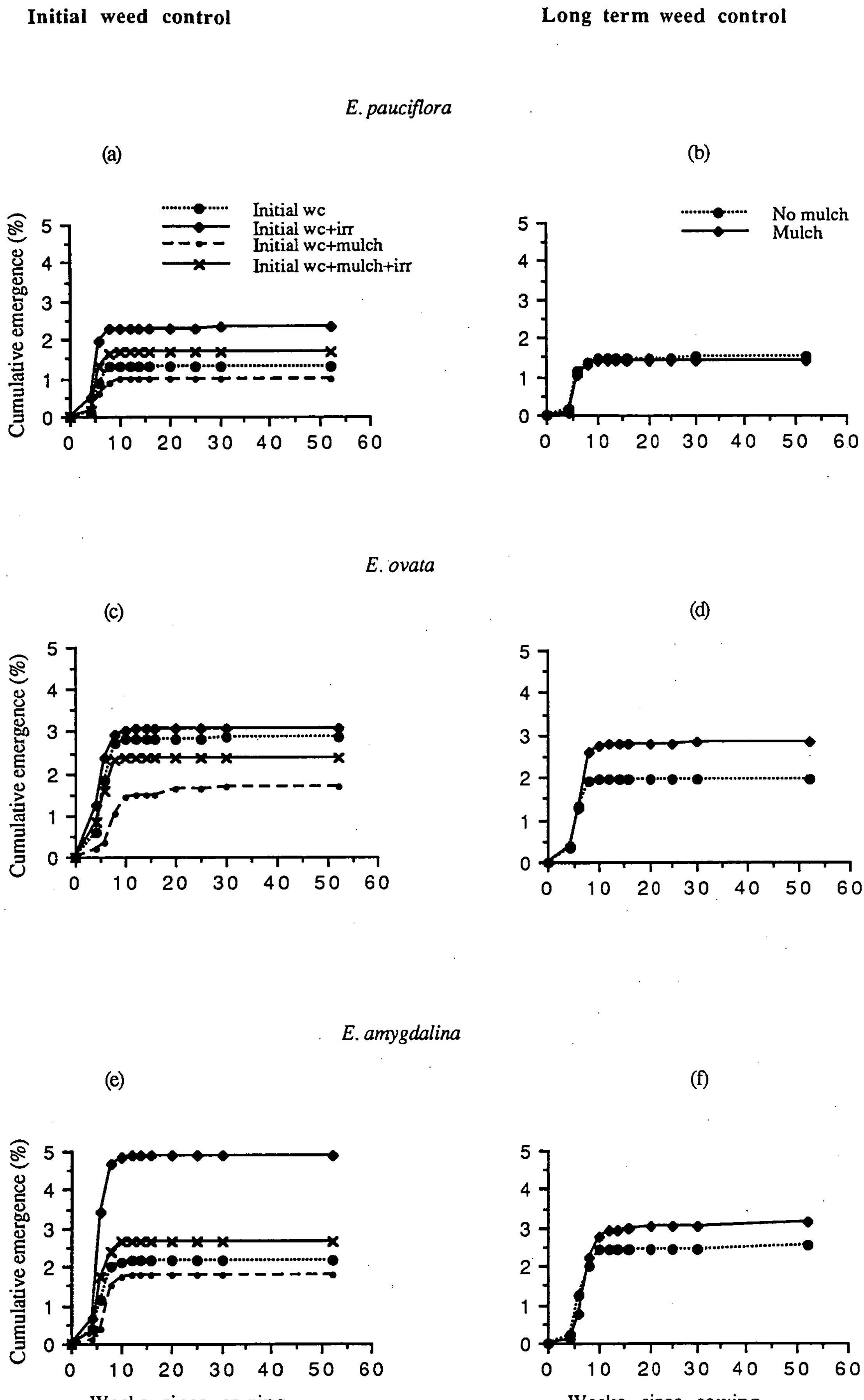


Figure 3.12. Effect of mulch addition on seedling emergence in the Cambridge field experiment, in plots with initial and long term weed control. Figures showing the effect of irrigation and mulch on emergence are unavialable.

Initial weed control

Long term weed control

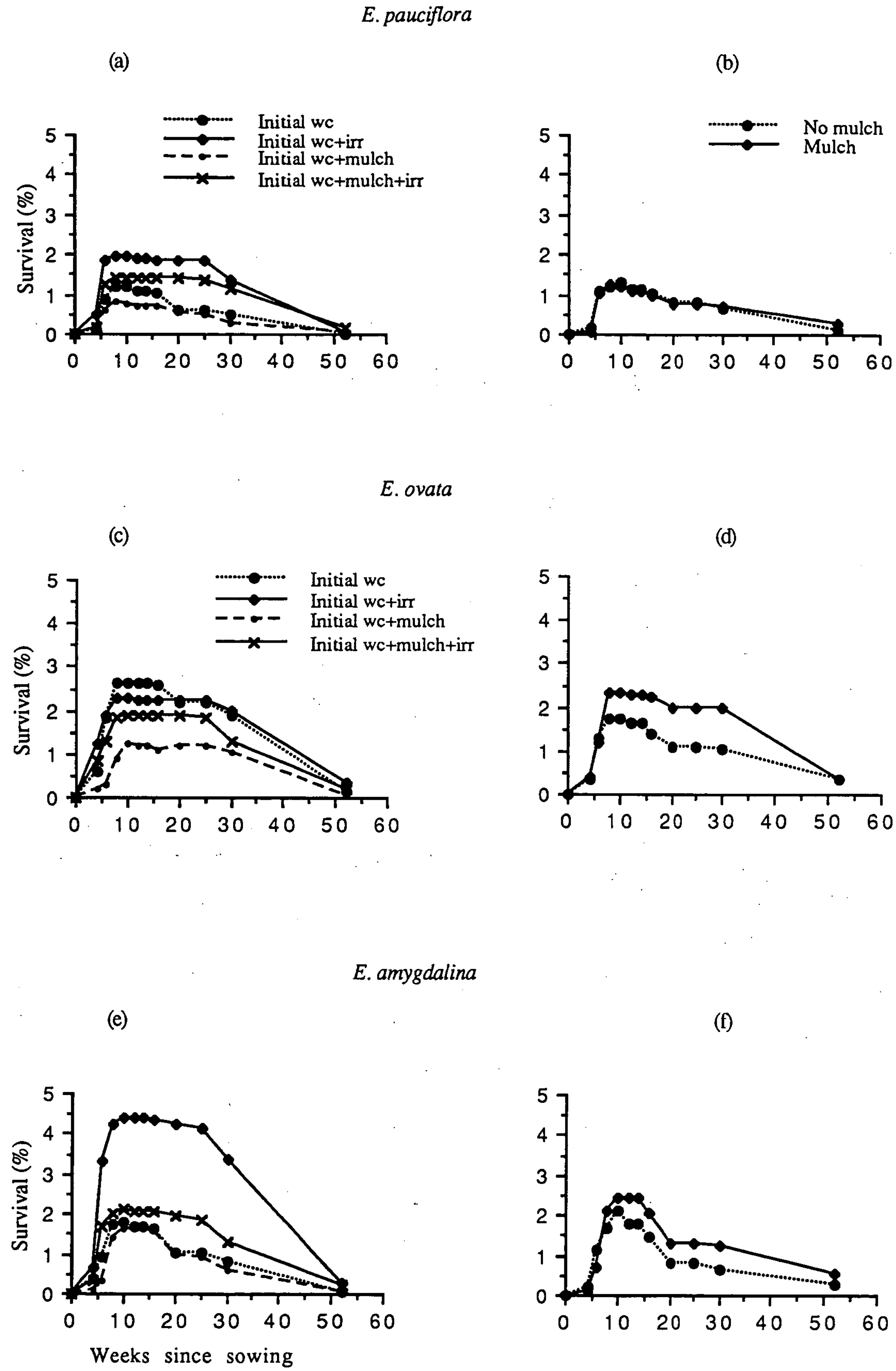


Figure 3.13. Effect of mulch addition on seedling survival in the Cambridge field experiment, in plots with initial and long term weed control. Figures showing the effect of irrigation and mulch on survival are unavailable.

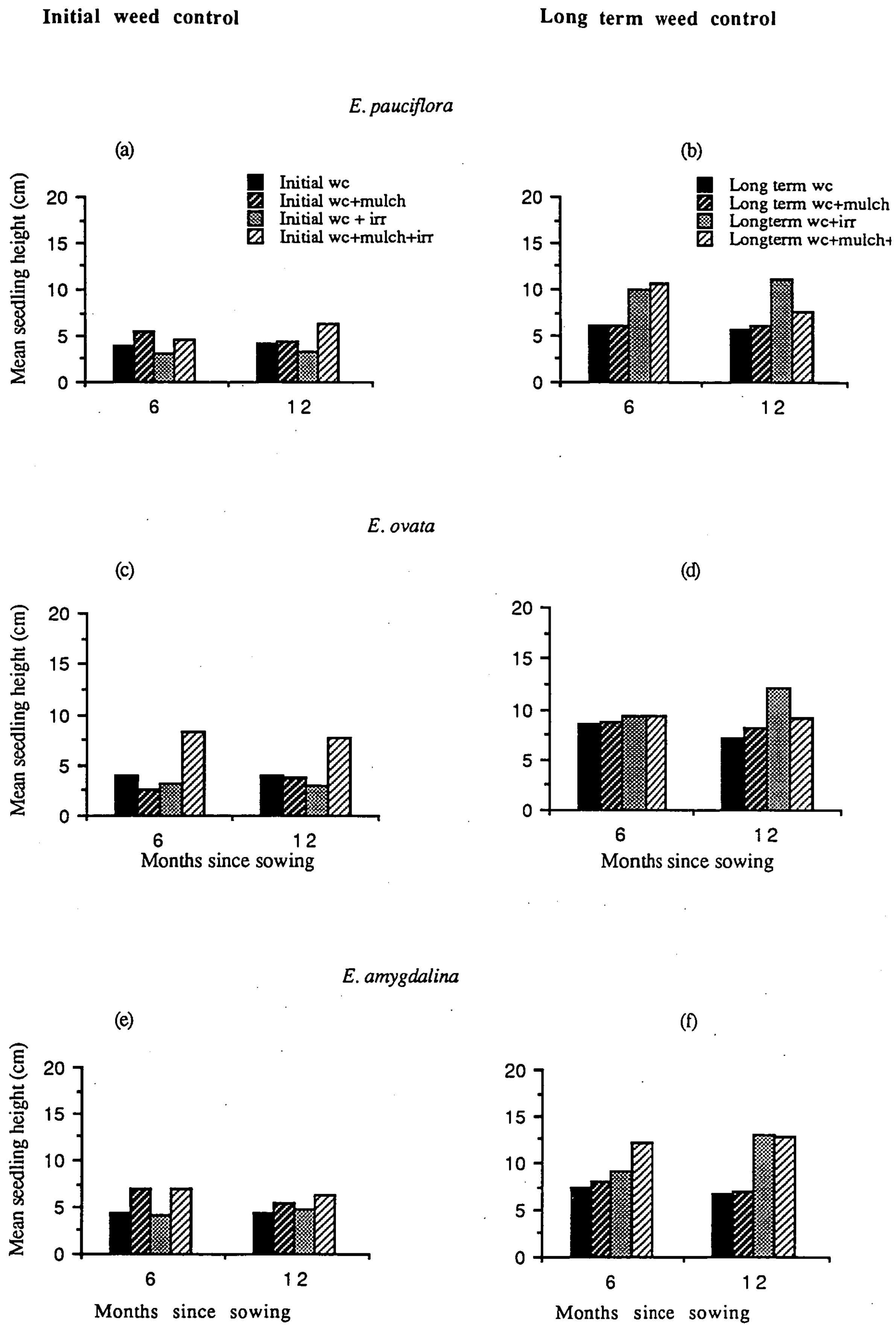


Figure 3.14. Effect of mulch addition mean seedling height in the Cambridge field experiment, in plots with initial and long term weed control.

Summary of Results

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* Irrigation increased emergence and survival although some species differences were apparent. This increase was recorded in weed control treatments (Tables 3.5, 3.6) and in fertilized (Tables 3.9, 3.10) and mulched plots (Tables 3.13, 3.14). Seedlings in plots with long term weed control responded to irrigation with increased growth after 12 months, although results were less consistent after 6 months (Table 3.8). *E. ovata* and *E. amygdalina* seedlings grown with initial weed control and fertilizer also displayed increased height after 6 months in response to irrigation (Table 3.11), as did *E. pauciflora* and *E. amygdalina* grown with long term weed control and mulch (Table 3.15).
* Long term weed control increased both emergence and survival compared to that recorded with no weed control, and was the only treatment to consistently increase seedling height.
* Fertilizer addition had no consistent effect on emergence, survival or height (Tables 3.9, 3.10, 3.11).
* Mulch addition had no consistent effect on emergence, survival or height (Tables 3.13, 3.14, 3.15).

Discussion

Irrigation

The increased emergence measured in response to irrigation is most likely to have been a direct consequence of increased moisture availability, but may also have been associated indirectly with soil cooling related to increased soil moisture content (Cunningham 1960; Roberts 1972; Zohar *et al.* 1975; Edgar 1977; Bachelard 1985; Gibson and Bachelard 1987). The optimum temperatures for germination of the three species in this experiment (Boland *et al.* 1980), and the soil temperatures measured at the site during October, the month of most germination, suggest that soil cooling associated with irrigation was probably not a factor influencing the emergence of *E. amygdalina* or *E. ovata*, although it may have been important for *E. pauciflora*.

The rate (speed) of emergence was not affected by irrigation, although other authors have recorded faster germination with increased moisture supply (Zohar *et al.* 1975; Gibson and Bachelard 1987). It may be that the time interval between scorings at Cambridge was too great to allow identification of subtle changes in rate which may have been observed from more frequent scorings. Alternatively, microsite variation may have been masking treatment effects. Many authors (Sheldon 1974; Harper 1977) have acknowledged the importance of microsites in reducing soil moisture loss and hence in increasing the opportunity for emergence and survival. It is possible that percentage emergence was greater with irrigation because the number of microsites with a suitable soil moisture content was greater than in unirrigated plots. Germination rate may not have been affected by irrigation because the moisture content of favourable microniches was similar both with and without irrigation.

Irrigation over the first summer significantly increased seedling survival after 12 months, but the increase was not very great. This may have been related to either the increased moisture supply or to soil cooling. Seedling numbers in all treatments fell after approximately 30 weeks, which coincided with the removal of irrigation. The trend was also apparent in unirrigated plots, and was probably related to the dry autumn and winter conditions. It is possible that if irrigation had continued through the winter, percentage survival may have been greatly increased. This has implications for the effectiveness of direct seeding in higher rainfall areas.

Irrigation did not significantly affect seedling height increment except in a few treatment combinations, which contradicts the findings of many other authors (Revell 1976; Revell and Deadman 1976; Cromer 1980. Nambiar and Zed 1980; Attiwill and Cromer 1982; Sands and Nambiar 1984). It is unlikely that the quantity of water provided was too low to stimulate growth, since the soil around irrigated seedlings was generally very moist. The increased density of weeds resulting from irrigation in plots with initial or no weed control probably increased competition for moisture. This does not explain the poor response to irrigation with long term weed control, although it could be that irrigation was stimulating root rather than shoot growth.

The inclusion of irrigation in the Cambridge experiment cost close to $500, although there was little gained in terms of seedling survival and height growth. In most situations it would be impractical to irrigate direct sown plantations, and there are some obvious dangers in removing irrigation after a period of time in unpredictable environments. It is possible that the results of direct seeding may be improved at sites with a greater mean annual rainfall than that experienced at Cambridge, although, as will become clear in the following discussion, the implications of increased weed competition resulting from greater soil moisture availability must be considered.

Weed control

Greater tree seedling growth has been reported in most instances where weed control has been conducted (Pryor and Clarke 1964; Nambiar and Zed 1980; Ellis *et al.* 1985; De Steven 1991b), particularly where rainfall is low or the water storage capacity of the soil is limited (Revell 1976). This experiment has illustrated the importance of some form of weed control to eucalypt emergence, survival and growth. The longer the weed control period, the better the survival and height growth. Initial weed control resulted in greater emergence than did no weed control, and often increased emergence above that recorded in plots with long term weed control. Survival and height were not, however, affected. Long term weed control resulted in a greater percentage emergence than no weed control, and increased both survival and height. With only a few exceptions, there was no seedling height increment in the last 6 months of the experiment except in plots with long term weed control and irrigation, which is contrary to the findings of other authors investigating tree establishment in dry environments (Nambiar and Zed 1980). Irrigation was disconnected early in the final 6 months of the experiment, which suggests that, for seedlings to exhibit a growth response after this time, they must have had greater access to nutrients and/or moisture than seedlings in other treatments. It may be that irrigation in the absence of weed competition stimulated root growth.

While all due care was taken when applying herbicide during long term weed control, it is possible that some eucalypt seedlings were poisoned in the process of weed elimination. This may explain the lower emergence recorded in plots with long term compared to initial weed control. There may also have been a greater proportion of seed harvested by insects in plots with long term weed control. Alternatively, the result may have been related to increased exposure and consequent greater soil surface temperatures and evaporation. Cunningham (1960) found that soil drying increased with the degree of exposure of mineral soil, and Nobel (1984) reported that shading decreased soil temperatures by as much as 11°C. De Steven (1991a) found that germination of some American hardwood species was less in weeded than in unweeded plots, which she attributed to increased exposure to unfavourable environmental conditions. However, at the Cambridge site, the weed density in plots with initial weed control was very low during the period of greatest emergence, which suggests that increased exposure was unlikely to have accounted for emergence differences.

The response to long term weed control may not have been related entirely to moisture availability, but could have been a consequence of reduced competition for available nutrients, as reported by Ellis *et al.* (1985). Factors such as allelopathy or adverse soil microflora may also have been important (Florence and Crocker 1962; Rice 1984).

Allelopathy involves the production by an organism of chemical compounds which, if present in appropriate concentrations, can affect the growth of other organisms (Rovira 1969; Rice 1984). Allelopathy is, however, difficult to distinguish from competition under field conditions. Often experiments to test for allelopathy have lacked realism, relying on the use of milled plant material and aqueous solutions of arbitrary concentrations (Cannon *et al.* 1962; Stowe 1979). Webb *et al.* (1983) found no evidence to support the hypothesis that growth check in *Eucalyptus delegatensis* was a result of the production of inhibitory allelochemes by *Poa labillardieri* (Steud.), and Ellis *et al.* (1985) suggested that this growth check may have instead been associated with nutrient deficiencies. Poor growth of *Eucalyptus pilularis* (Sm.) was found by Florence and Crocker (1962) to be related to lack of available nutrients and to the presence of antagonistic microflora.

The slow growth rates recorded at Cambridge may have been associated with a lack of appropriate mycorrhizal associations. Many Australian plant species are known to form symbiotic relationships with soil mycorrhizae (Warcup 1980), and the absence of suitable mycorrhizae has been demonstrated in many cases to reduce the growth of tree seedlings (Harris and Jurgensen 1977; Malazcjuk *et al.* 1981; Abbott and Robson 1982; Abbott and Robson 1984; Jasper *et al.* 1989a). Jasper *et al.* (1987) found that discing a prairie soil, which both disturbed the soil and destroyed plant growth, decreased the subsequent colonization by vesicular arbuscular mycorrhizae of plants grown in that soil. Similarly, Jasper *et al.* (1989a) found that the infectivity of propagules of vesicular arbuscular mycorrhizal fungi in topsoil in Western Australia was destroyed during the stripping process associated with bauxite mining and during land clearing. They suggested that mycorrhizal infectivity depends largely on propagules remaining attached to living plants. Lewis (1980) considers that the addition of large amounts of fertilizer may be detrimental to the re-establishment of soil mycorrhizae. Thus it is possible that propagules of soil mycorrhizae able to form associations with eucalypts were either absent or present in only low numbers at Cambridge, with consequent poor seedling growth.

Fertilizer

Fertilizer addition had no consistent effect on emergence or survival of eucalypt seedlings, although mean seedling height in some treatments for some species was slightly greater after 6 months if fertilizer had been applied. Lockett (1978) also found that emergence of *Eucalyptus obliqua* was unaffected by field applications of fertilizer at the time of sowing. However, most authors have reported significant growth responses of eucalypt seedlings to added fertilizer (Fielding and Brown 1961; McIntyre and Pryor 1974; Flinn *et al.* 1979; Cromer *et al.* 1981; Ward *et al.* 1985; Schonau and Herbert 1989). Increased growth in response to added macronutrients has also been measured in conifers. It is possible that in the present experiment fertilizer was added at a rate too low to influence emergence, survival or growth, particularly given the likely high nutrient status of this improved pasture soil. Schonau and Herbert (1989) recommend applying fertilizer at 10 to 20 grams tree^{-1}, whereas fertilizer was added at Cambridge at a rate of 20 grams metre^{-2}, which was equivalent to much less per tree.

Fertilizer may have been applied at an inappropriate time. Although the fertilizer was of a slow release nature, much of it may have leached from the upper soil before it could be utilized by emerging seedlings. Alternatively, weed species may have absorbed most of the extra nutrients. The effect of fertilizer addition on seedling growth in plots with long term weed control was not tested.

In instances where increased height was measured in plots with fertilizer addition, such a response was, with only one exception, no longer apparent after 12 months, undoubtedly due to losses either by leaching or plant utilization. Subsequent fertilizer applications may have increased seedling height, although it can be expected that this would be most effective in combination with weed control.

Wight and Black (1987), Lahiri (1980) and Schonau and Herbert (1989) discuss the promotion of root growth by fertilizer addition. Increased root growth associated with fertilizer application can facilitate extraction of water from deeper in the soil, and can promote growth when moisture is limiting. However, this phenomenon is common to both tree and weed species, and Wight and Black (1987) found that fertilizer application can significantly increase the productivity and subsequent water use efficiency of grassland ecosystems. It is possible that monitoring only shoot height does not give an accurate indication of the effect of fertilizer addition on seedling growth.

Mulch

Mulch can have both positive and negative effects on seedling emergence and growth. It can increase microsite variation and the number of safe sites for germination, which can critically affect emergence and survival, particularly when environmental conditions are unfavourable (Sheldon 1974; Harper 1977). Microsite variation can provide protection to seed from browsing organisms, can increase available moisture in the soil/seed interface, may increase soil/seed contact, and may reduce surface crust formation. It can also protect emergents from tissue damage resulting from high or low temperatures (Nobel 1984). Mulch can also reduce soil temperatures and increase the severity of frosts (Hall 1985).

In this experiment, mulching significantly decreased cumulative emergence in plots with initial weed control, and had no consistent effect on survival. However, emergence was not reduced by the presence of mulch in plots with long term weed control, and survival of *E. pauciflora* and *E. amygdalina* was actually greater in mulched than in unmulched plots. This is difficult to explain. It could be that in plots with weeds present, mulch reduced soil temperature more than in plots with long term weed control, or that there was greater competition for light due to better utilization by weeds of the available soil space. Because mulch had no negative effect on emergence in plots with long term weed control, the leaching of tannins or other substances from the mulch material is not likely to have been a factor influencing results.

In plots with initial weed control, mulching, with only one exception, increased mean height after 6 months, both with and without irrigation. It is possible that mulch either decreased the density of weeds in plots with initial weed control, thus reducing competition between weeds and eucalypt seedlings, or that it increased the soil moisture level by reducing surface evaporation, thereby stimulating growth. When mulch was added to plots with long term weed control, there was no effect on height after 6 months, which suggests that any increased water content in mulched plots was not critical when long term weed control was applied. After 12 months, the presence of mulch in irrigated plots with long term weed control reduced the height of all species, although the difference was not significant for *E. amygdalina*. This is difficult to explain, but may be related to lower soil temperatures under mulch, which may have decreased eucalypt root and shoot growth. Hall (1985) recorded reduced root and shoot growth in mulched *P. radiata* seedlings.

The type of mulch used may influence the results achieved. Duckett (1987) and Hinz (1990) both recommend slash material as mulch when direct seeding in harsh environments, which would probably provide greater protection to emerging seedlings than wood chips and may therefore have been a more suitable material to use at the Cambridge site. Slash, however, may significantly decrease soil temperature and light available to emergents. In South Australia, bitumen mulch has been used successfully on some sites (Dalton 1990). As well as reducing soil water evaporation, this mulch has the added advantage of increasing the soil temperature around the seed, which has been found to promote earlier germination at a more rapid rate. Geiger (1966), however, cautions that dark colours at the soil surface may increase the incidence of frost, another factor likely to be of significance at the Cambridge site.

Weather

The temperature gradient of the air increases substantially towards the soil surface, and particularly in the 10 cm closest to the ground, where the greatest extremes in temperature are often recorded. Geiger (1966) reported air temperatures of 16°C at 1.5 metres height, 17°C at 50 cm, 19°C at 10 cm, and 25°C at 1 cm. Nobel (1984) measured maximum air temperatures of 47.5°C 1 cm above the soil and 43°C at 5 cm. The soil temperature at the same time was 59.1°C. Thus, when maximum air temperatures close to 50°C were recorded at 10 cm height at Cambridge, it is likely that temperatures at the soil surface/air interface were greater than this. Smaller seedlings in particular at the Cambridge site may have experienced tissue damage related to higher air temperatures, lower wind speeds and greater conduction from the soil on hot days. Cunningham (1960), Cremer (1962) and

Fagg (1981) reported most mortality of eucalypts due to high temperatures when the seedlings were still at the cotyledonous stage, and Nobel (1984) considers that seedling tolerance to high or low temperatures may increase with age or size. This highlights the importance of stimulating early seedling growth.

As well as high temperatures, low temperatures can contribute to seedling mortality. Freezing of plant parts may result in dehydration and/or cell wall rupture, making recovery after thawing difficult (Fagg 1981). Tibbits (1986) found that temperatures at which 50% tissue damage occurred in 13 eucalypt species were -6°C or below in winter, and -2.5°C or below in summer. Fagg (1981) found that complete death due to freezing was confined in three eucalypt species to seedlings with up to two leaf pairs, although Grose (1957) recorded losses in larger seedlings of *E. delegatensis*. Cremer (1962), however, concluded that soil heave was a more serious consequence of frost than tissue damage. At the Cambridge site, frosts were frequent in winter, and the increased incidence of frosts leading into winter coincided with increased seedling mortality. In the other seasons temperatures rarely fell below zero, suggesting that frost damage during this period was probably minimal.

Species

Although there was some variation, the lowest cumulative emergence was recorded for*E. pauciflora*, and the greatest for *E. amygdalina*. The low emergence of *E. pauciflora* may be explained in terms of stratification requirements. Fagg (1981) recorded a lower percent emergence of *E. delegatensis* in spring sowings, and attributed it to the lack of a period of cool moist stratification. In the viability tests outlined in Appendix 2, *E. pauciflora* responded significantly to cool moist stratification for 3 weeks, with stratified seed showing double the percent and a faster rate of germination.

Bachelard (1985) noted, in studies with three eucalypt species, that smaller seeds have a larger proportion of the seed coat in contact with the soil surface and a smaller proportion exposed to evaporative stress, which resulted in a more favourable water balance for germination. He found that germination percent of *Eucalyptus sieberi*, a small-seeded eucalypt, was greater than that of two larger-seeded species, *Eucalyptus pilularis* and *Eucalyptus maculata* (Hook.). In the germination tests outlined in Appendix 2, germination percent was greater and rate of germination was faster in *E. ovata*, a small-seeded species, than in *E. pauciflora* or *E. amygdalina*, which have larger seeds. This does not explain why the percentage emergence of *E. amygdalina* was greater than that of *E. ovata* in the Cambridge trial. Bewley and Black (1982) note that factors other than seed size affect a species ability to germinate under conditions of water stress, such as seed morphology and degree of suberization. It may also be that at the Cambridge site there was preferential browsing of *E. ovata* seed (Appendix 3).

Other

While cumulative emergence was in all cases much lower than that recorded in laboratory viability tests (Appendix 2), the seeds were subjected to more harsh environmental conditions than would be experienced in a laboratory. Survival recorded by Cunningham (1960) was 0.8-1.8% after 1 year. The percent survival recorded in this experiment was similar to this.

Height growth at Cambridge was generally very slow, although it may be all that is achievable on harsh sites. Battaglia (1990a), for example, recorded poor growth of eucalypt seedlings growing at high altitudes or on sites with a grassy understorey.

Conclusions

Long term weed control has been demonstrated in this experiment to be very important in increasing emergence, survival and height of direct-sown seedlings. It is unclear whether this is a response to reduced competition for moisture or nutrients, but it is probably at least a partial response to both. It may also be due to other factors such as allelopathy or adverse soil microflora associated with weed species. Irrigation increased both emergence and seedling survival, perhaps suggesting that direct seeding would be more successful in wetter areas of the state, but only if long term weed control was achieved. Fertilizer had no consistent effect on emergence or survival, and only slightly increased height after 6 months. Possibly a greater height response to fertilizer may have been measured if the fertilizer was added post-emergence. How fertilizer was affecting root growth is unclear. It would, however, seem that adding fertilizer at the time of sowing offered few advantages at the Cambridge site.

Figure 3.15. A view of the Cambridge field plot, taken immediately prior to sowing, showing irrigation lines running down the slope.

CHAPTER 4. An investigation of possible causes of poor establishment.

Introduction

While field experiments are useful in determining general silvicultural treatment effects on species emergence, growth and survival, they are not without problems. Because of the interaction in the field of many uncontrolled factors, treatment means can be obscured by experimental noise. In addition, field experiments often preclude the intensive monitoring that is possible in glasshouse experiments. Field experiments potentially give realistic results, but may not allow accurate definition of processes.

In glasshouse experiments, detailed measurement of a number of growth parameters is possible. The effect of specific treatments on these growth parameters can often be more clearly distinguished than in the field, and it may be possible to determine reasons for particular growth responses. The results of glasshouse experiments may not, however, be relevant in the field, and for this reason both types of experimentation are desirable.

In the previous chapter, weed control and irrigation were shown to have a significant effect on the emergence, survival and growth of three eucalypt species. Reasons for this response were unclear. The experiments in this chapter were established with the following aims:

1. to determine the relative importance of weed control and irrigation on establishment;
2. to ascertain whether the response to weed control was related to competition for nutrients or moisture, or to unfavourable soil biology.

An experiment was established to investigate the effect of factorial combinations of fertilizer, weed control and irrigation on the germination and growth in pasture soil of one eucalypt species. Growth was compared with that achieved in commercial potting mix. In addition, germination and growth were measured in heat sterilized pasture soil and soil collected from a remnant bushland block.

Eucalyptus amygdalina was perhaps the most successful species in the field experiment of Chapter 3. As its seeds are large in eucalypt terms, it is relatively easy to work with, and previous germination tests (Appendix 2) showed that stratification prior to sowing was not necessary. For these reasons, *E. amygdalina* was chosen as a suitable species for these glasshouse experiments.

Experiment 1. Response of *E. amygdalina* to factorial combinations of weed control, irrigation and fertilizer.

Methods

'A' horizon soil was collected in early December 1990 from the University farm at Cambridge (see Appendix 1 for site description). It was sieved to remove organic particles and rock with a diameter greater than 0.5 cm, and placed into eighty 15 x 15 cm plastic pots. Ten pots were filled with commercial potting mix. The soil was then saturated with water, and the pots were placed in a glasshouse with a mean minimum temperature of 7.5°C and a mean maximum of 30°C. The experiment was established as a completely randomised factorial design, with 2 irrigation (+, -), 2 fertilizer (+, -) and 2 weed control (+, -) treatments, and replicated 10 times.

Ninety seed samples of three grams were taken from an *E. amygdalina* seed mix comprising equal proportions of seed collected from Fingal, Royal George and Avoca (see Appendix 2 for a description of the germination characteristics of these provenances). From each 3 gram sample, 25 seeds were randomly removed and sown onto the soil in one of the prepared pots.

Ten pots were allocated as 'controls', and no further treatment was applied. The 10 pots filled with potting mix were used to compare the height growth of seedlings in pasture soil to that in a known healthy soil medium ('potting mix'). These pots were irrigated daily and weeded weekly.

Approximately 2 grams of Osmocote® slow release fertilizer was then added to the 40 pots in the fertilizer treatment (approximately 113 kg ha^{-1}). Osmocote® consists of 14% nitrogen (present as nitrate and ammonium), 6.2% phosphorus (present in water-soluble and citrate-soluble forms), 11% potassium, 4.5% sulphur and 5% calcium.

The 50 pots allocated to the irrigation treatment were saturated daily, and those in unirrigated treatments were given approximately 2 litres of water once per week. All water was added as a fine mist during germination, but in the second phase of the experiment, water was dribbled over the edge of each pot, to avoid wetting the eucalypt foliage.

Pots in weed control treatments were hand weeded weekly.

Seed germination was monitored every 1 - 3 days for 26 days, at which time germination was considered to be complete. At this stage, seedlings were thinned to 1 per pot, of approximately 0.5 cm height, and subsequent height growth was monitored. After 7 weeks, the seedlings were harvested. The soil was removed from the roots of the eucalypt and weed seedlings, by soaking each pot of soil in water and gently washing the soil from the roots. Some root damage can be expected to have occurred using this technique, including loss of fine roots and root hairs. The root and shoot length of eucalypt seedlings was measured, and both eucalypt and weed seedlings were oven dried at 60°C for 12 hours, after which time weight was found to be constant and final weights were recorded.

Shoot material from eucalypt seedlings in each irrigation treatment was bulked, and sent to the Department of Primary Industries Mt Pleasant laboratory for analysis of the concentrations of phosphorus, potassium, zinc, boron, iron, calcium, magnesium, sodium, sulphur, manganese, copper and nitrogen. The total sample for 3 of the treatments was insufficient to allow nitrogen sampling.

Rate of germination was determined by estimating the time taken to achieve 10%, 50% and 90% final cumulative germination.

Data were analysed using the General Linear Model procedure in SAS (SAS Institute Inc 1989a, b). Germination data were converted into percentages, and arcsine transformed as recommended by Sokal and Rohlf (1969). Residual data analysis indicated heteroscedacity, and seedling height, root length, root to shoot ratio and biomass data were normalized by log transformation before analysis of variance (McPherson 1990).

Results

Germination

Irrigation ($P<0.0001$) and the combination of irrigation and weed control ($P<0.03$) significantly influenced mean germination (Table 4.5). Irrigation increased germination, whereas fertilizer addition decreased it (although the decrease was not significant in irrigated pots) (Table 4.1, Figures 4.1, 4.2). Weed control decreased germination in unirrigated pots, but when irrigation was applied the germination percent did not differ between pots with only irrigation and those with weed control. While there was little difference in the rate of germination in any treatment, adding fertilizer in the absence of irrigation considerably decreased the time to achieve 90% germination, although this was not statistically significant (Table 4.2, Figure 4.2).

Table 4.1. Mean germination percent recorded with combinations of irrigation, weed control and fertilizer. Numbers in brackets indicate confidence intervals. Different letters indicate treatment differences (P<0.05). N = 10.

Treatment	Mean Germination (%)
Control	11.24^{c} (9.27-13.38)
Weed control	3.11^{de} (1.68-4.96)
Fertilize	5.64^{d} (4.33-6.65)
Weed cont+fert	2.64^{e} (1.45-4.17)
Irrigate	20.44^{ab} (17.77-23.32)
Irr+weed control	24.22^{a} (22.07-26.44)
Irr+fertilize	15.98^{bc} (13.13-19.05)
Irr,Weed+fertilize	17.11^{b} (14.46-19.82)

Table 4.2. Rate of germination (days) with combinations of irrigation, weed control and fertilizer, measured as time in days to achieve 10, 50 and 90% germination. Different letters in each column indicate treatment differences (P<0.05).

Treatment	Mean germination rate (days)		
	*t10**	*t50*	*t90*
Control	5.5^{a} (2.0-7.0)	10.5^{a} (4.0-14.0)	17.0^{a} (11.0-20.0)
Fertilize	6.0^{a} (4.5-7.0)	9.5^{a} (5.0-10.0)	11.0^{a} (6.5-12.5)
Weed control	5.5^{a} (1.5-10.0)	12.5^{a} (7.0-16.0)	16.5^{a} (12.0-17.5)
Weed control+fert	5.5^{a} (1.5-9.5)	9.5^{a} (7.0-15.0)	18.0^{a} (9.0-19.0)
Irrigate	4.5^{a} (1.0-12.0)	11.0^{a} (4.5-13.0)	15.0^{a} (13.0-18.5)
Irr+fertilize	3.0^{a} (0.5-5.0)	9.0^{a} (2.0-11.0)	14.0^{a} (3.0-17.0)
Irr+weed control	4.5^{a} (2.0-5.0)	10.5^{a} (4.0-12.0)	14.5^{a} (8.0-19.5)
Irr,weed cont+fert	3.5^{a} (1.5-5.0)	9.5^{a} (4.0-11.0)	16.0^{a} (9.5-22.0)

* *t10* = number of days to 10% germination; *t50* = number of days to 50% germination; *t90* = number of days to 90% germination

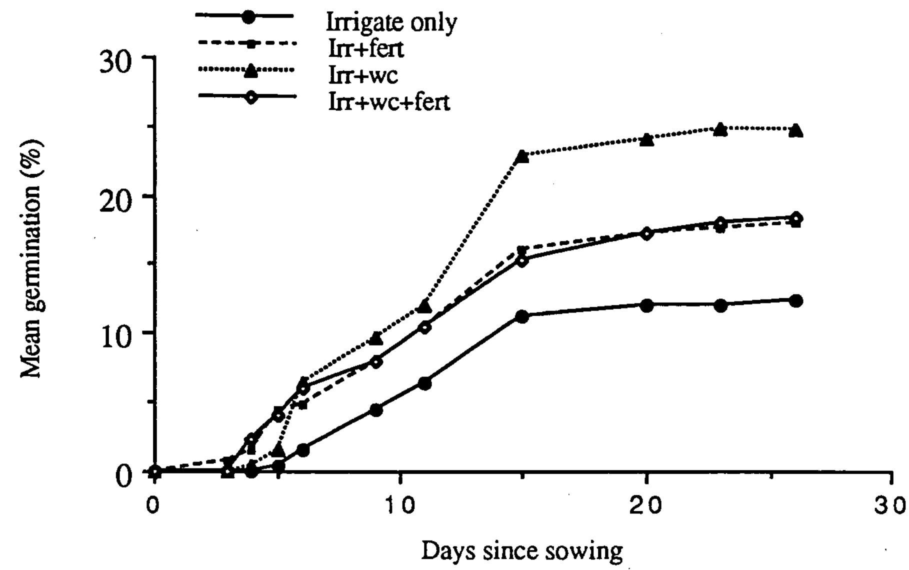

Figure 4.1. Mean germination percent of *E. amygdalina* growing with combinations of irrigation, weed control and fertilizer. Irr = irirgate; fert = fertilize; wc = weed control.

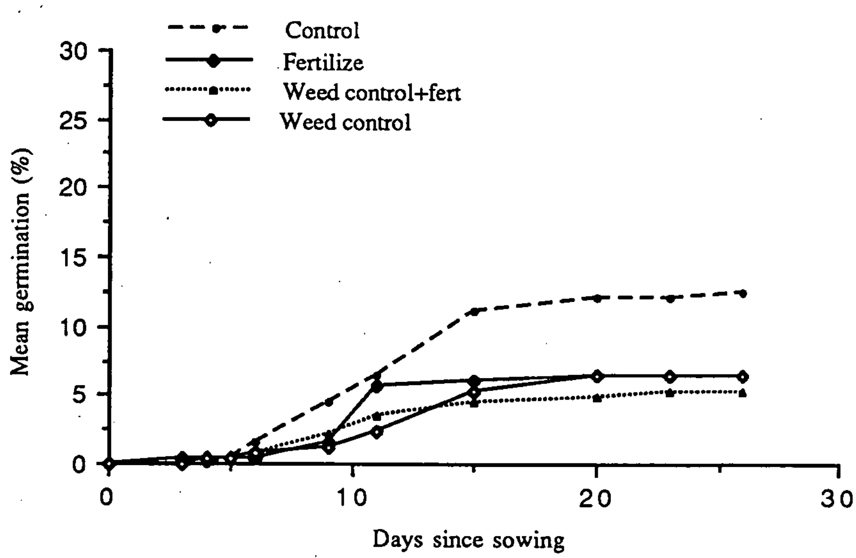

Figure 4.2. Mean germination percent of *E. amygdalina* growing with combinations of weed control and fertilizer, and no irrigation. Fert = fertilize.

Height

Irrigation ($P<0.0001$), fertilizer ($P<0.0001$), weed control ($P<0.01$), or the combination of irrigation and fertilizer ($P<0.01$) or fertilizer and weed control ($P<0.005$) significantly influenced mean seedling height (Table 4.5). Irrigation, or the combination of irrigation and fertilizer (Table 4.3) significantly increased mean seedling height (Table 4.3, Figures 4.3, 4.4). The combination of irrigation, weed control and fertilizer, however, resulted in the greatest mean seedling height, being four times greater than that recorded in the 'irrigate only' treatment, and twice as great as the mean height of the combination of the two, the next best performing treatment (Table 4.3). Height in this treatment after 7 weeks was also greater than that of seedlings grown in potting mix. The growth rate in this treatment was approximately twice the average growth rate of the other irrigated treatments (1.78 cm $week^{-1}$ compared with 0.80 cm $week^{-1}$), and approximated the exponential growth expected in the early development of healthy plants (Salisbury and Ross 1978) (Figure 4.3).

In unirrigated treatments, the combination of fertilizer and weed control also increased mean seedling height, although not to the extent recorded in irrigated pots (Table 4.3, Figure 4.4). There was no difference between the heights of the other unirrigated treatments. Without irrigation, the combination of weed control and fertilizer resulted in a growth rate of 0.65 cm $week^{-1}$, compared to an average growth rate in the other unirrigated treatments of 0.41 cm $week^{-1}$. Figure 4.4 illustrates substantial differences in the growth rates of the four unirrigated treatments, with only the combination of weed control and fertilizer resulting in exponential growth. Interestingly, the growth rate of seedlings grown in potting mix (with irrigation) was only greater than that of seedlings grown with weed control and fertilizer (no irrigation) in the last week of the experiment, although differences would probably have increased if the experiment had been continued.

In most treatments, all seedlings were less than 5 cm high at the conclusion of the experiment (Figure 4.5). The combination of irrigation and fertilizer, or weed control and fertilizer in the absence of irrigation, slightly increased the seedling height range, but seedlings were still all less than 10 cm at the end of the experiment. Only the combination of irrigation, weed control and fertilizer, resulted in a wide range of seedling sizes (0 - 20 cm) (Figure 4.5).

Table 4.3. Mean height of seedlings grown with combinations of weed control, irrigation and fertilizer addition ($P<0.05$). Different letters indicate treatment differences. $N \geq 9$.

Treatment	Mean Seedling Height (cm)
Control	2.96^{d} (2.72-3.23)
Weed control	2.74^{d} (2.54-2.95)
Fertilize	3.03^{d} (2.80-3.28)
Weed cont+fert	4.57^{bc} (3.64-5.72)
Irrigate	3.62^{c} (3.42-3.82)
Irr+weed control	3.72^{c} (3.63-3.83)
Irr+fertilize	5.81^{b} (5.18-6.51)
Irr,Weed+fertilize	12.48^{a} (11.15-13.96)

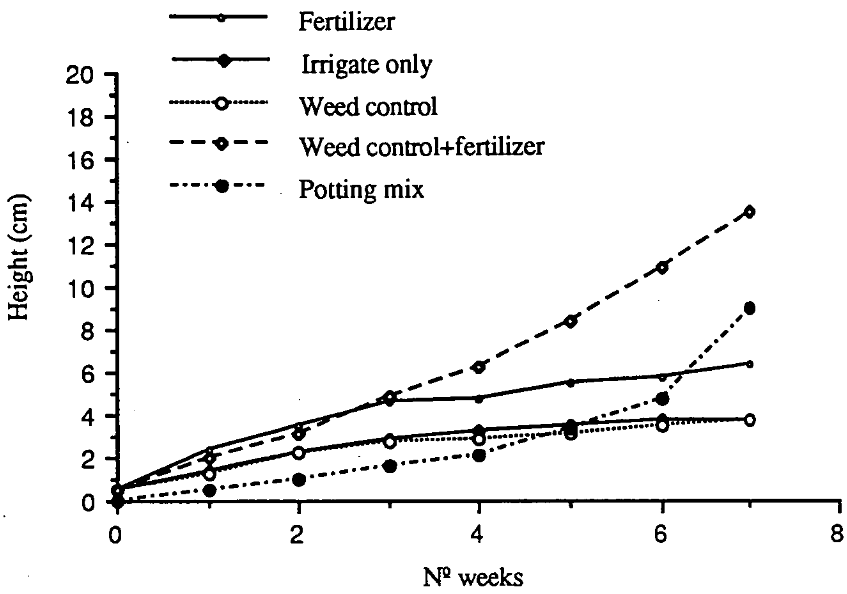

Figure 4.3. Mean height of seedlings (cm) growing with combinations of irrigation, weed control and fertilizer.

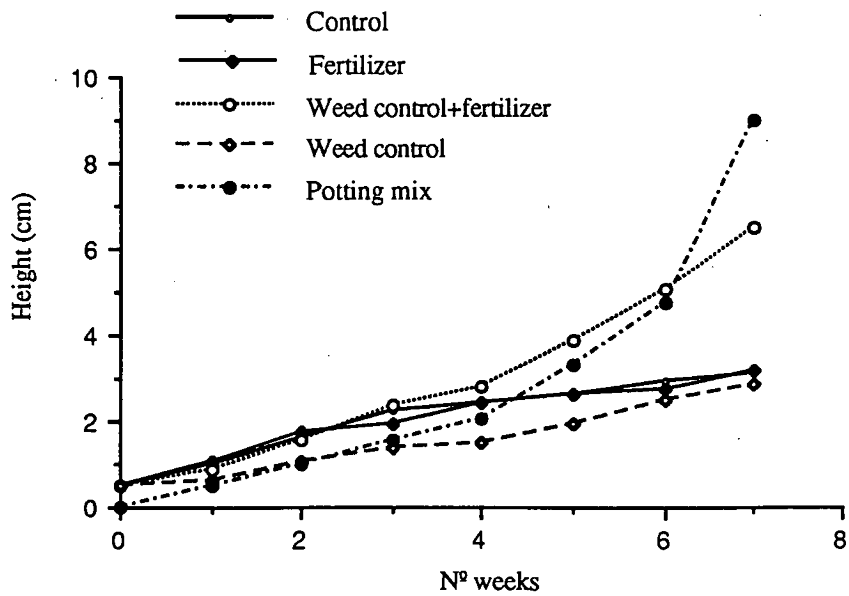

Figure 4.4. Mean height of seedlings (cm) grown in combinations of weed control and fertilizer, with no irrigation.

Table 4.5. ANOVA table of the effects of irrigation, weed control and fertilizer on seedling establishment.

Source of Variation	DF	MS	F	p
(a) Germination				
Irrigation	1	1.006	42.77	0.0001
Fertilize	1	0.087	3.72	0.0576
Weed control	1	0.038	1.62	0.2067
Irrigate x fertilize	1	0.001	0.03	0.8561
Irrigate x weed control	1	0.109	4.63	0.0348
Fertilize x weed control	1	0.004	0.20	0.6541
Irrigate, fertilize, weed control	1	0.018	0.79	0.3778
RESIDUAL	71	0.023		
(b) Seedling Height				
Irrigate	1	5.180	25.99	0.0001
Fertilize	1	5.452	27.36	0.0001
Weed control	1	1.402	7.04	0.0100
Irrigate x fertilize	1	1.461	7.33	0.0087
Irrigate x weed control	1	0.239	1.20	0.2767
Fertilize x weed control	1	1.658	8.32	0.0053
Irrigate, fertilize, weed control	1	0.068	0.34	0.5604
RESIDUAL	65	0.199		
(c) Weed Biomass				
Irrigate	1	3.428	29.00	0.0001
Fertilize	1	1.101	9.31	0.0045
Irrigate x fertilize	1	0.051	0.48	0.4938
RESIDUAL	33			
(d) Eucalypt Biomass				
Irrigate	1	1.793	1.24	0.2701
Fertilize	1	1.664	1.15	0.2878
Weed control	1	25.137	17.36	0.0001
Irr x fertilize	1	4.167	2.88	0.0949
Irr x weed control	1	3.675	2.54	0.1163
Fert x weed control	1	1.624	1.12	0.2937
Irr x fert x weed control	1	16.304	11.62	0.0014
RESIDUAL	61	1.448		
(e) Root Length				
Irrigate	1	1.223	6.90	0.0110
Fertilize	1	1.366	7.70	0.0074
Weed control	1	1.082	6.10	0.0164
Irrigate x fertilize	1	2.063	11.63	0.0012
Irrigate x weed control	1	0.018	0.11	0.7452
Fertilize x weed control	1	0.134	0.76	0.3882
Irrigate, fertilize, weed control	1	0.503	2.84	0.0974
RESIDUAL	59	0.177		
(f) Root to Shoot Length Ratio				
Irrigate	1	0.190	0.85	0.3610
Fertilize	1	0.984	4.38	0.0406
Weed control	1	0.689	3.07	0.0851
Irrigate x fertilize	1	0.204	0.91	0.3438
Irrigate x weed control	1	0.015	0.07	0.7962
Fertilize x weed control	1	0.661	2.94	0.0916
Irrigate, fertilize, weed control	1	3.431	15.27	0.0002
RESIDUAL	59	0.224		

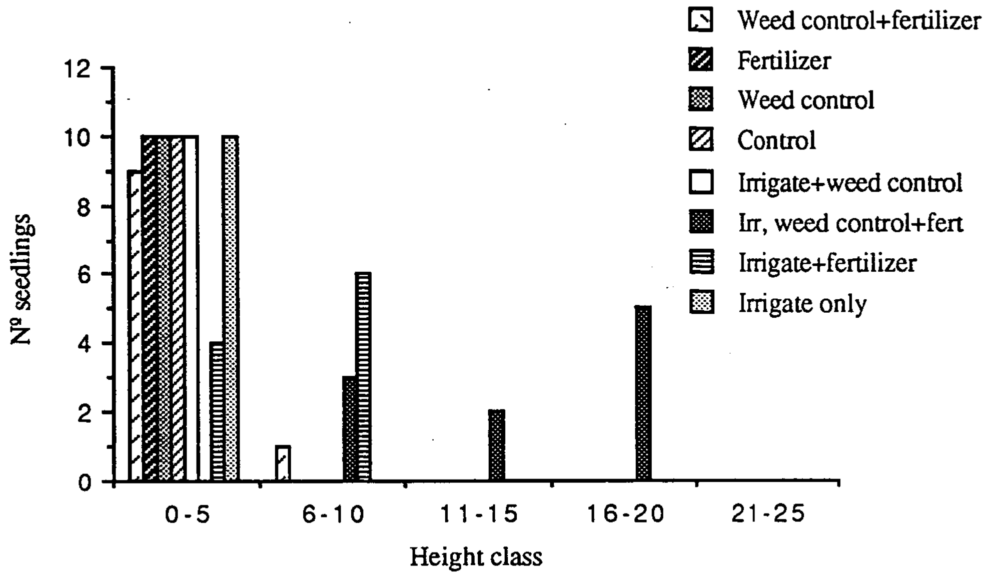

Figure 4.5. Variation in height distribution of *E. amygdalina* seedlings growing with combinations of irrigation, weed control and fertilizer.

Eucalypt Biomass

Eucalypt seedling above- and below-ground biomass was significantly influenced by the level of weed control ($P<0.0001$) and the interaction of irrigation, weed control and fertilizer ($P<0.001$) (Table 4.5). In unirrigated pots, no treatment significantly affected biomass (Table 4.6).

When irrigation was applied, weed control resulted in a substantially greater mean seedling weight than the other treatments (a minimum of 8 times greater). The mean weight of seedlings grown with weed control, irrigation and fertilizer was approximately half that of seedlings grown with weed control, fertilizer and no irrigation. Similarly, seedlings grown with only irrigation had approximately half the mean weight of seedlings grown in control pots, although the difference was not statistically significant ($P<0.05$). The ranking of weights in irrigated treatments did not approximate height rankings, with the greatest weight being recorded in the treatment which had one of the lowest mean heights (compare Tables 4.3 and 4.6).

Not too much emphasis has been placed on these data, as there appeared to be little consistent trend. Loss of root material during the washing process may have contributed to this.

Table 4.6. Mean seedling weight (grams) for treatments with combinations of weed control, irrigation and fertilizer ($P<0.05$). Different letters indicate treatment differences. $N \geq 7$

Treatment	Mean Seedling Weight (gm)
Control	0.04[bcd] (0.02-0.07)
Weed control	0.05[bcd] (0.02-0.08)
Fertilize	0.02[d] (0.02-0.03)
Weed cont+fert	0.12[b] (0.07-0.18)
Irrigate	0.02[d] (0.02-0.02)
Irr+weed control	0.49[a] (0.41-0.58)
Irr+fertilize	0.04[cd] (0.03-0.05)
Irr,weed+fertilize	0.06[c] (0.05-0.06)

Root Length

The mean length of the longest seedling root was significantly influenced by irrigation ($P<0.01$), weed control ($P<0.01$) and fertilizer ($P<0.02$), and by the combinations of irrigation and fertilizer ($P<0.001$) and of all three ($P<0.001$) (Table 4.5). In the absence of irrigation, the combination of weed control and fertilizer resulted in a mean root length more than twice that measured for seedlings in control pots (Table 4.7). Fertilizer addition alone also significantly increased mean root length. The addition of weed control alone did not alter the root length.

When irrigation was applied, the weed control treatment resulted in the greatest mean root length. The fertilizer and fertilizer plus weed control treatments both resulted in greater mean root lengths than the control (Table 4.7).

The addition of irrigation increased mean seedling root length above that recorded in unirrigated pots in all treatments except where fertilizer was applied.

Table 4.7. Mean root length (cm) measured with combinations of irrigation, weed control and fertilizer ($P<0.05$). Different letters indicate treatment differences. $N \geq 6$.

Treatment	Mean Root Length (cm)
Control	6.62^{d} (5.40-8.11)
Weed control	7.60^{d} (7.19-8.03)
Fertilize	11.59^{bc} (10.46-12.84)
Weed cont+fert	15.78^{a} (14.76-17.10)
Irrigate	10.07^{c} (9.19-11.04)
Irr+weed control	17.61^{a} (15.84-19.57)
Irr+fertilize	12.30^{b} (11.10-13.65)
Irr,Weed+fertilize	12.62^{b} (11.96-13.31)

Root to Shoot Length Ratio

The mean root to shoot length ratio was significantly influenced by fertilizer addition ($P<0.04$), and by the interaction of irrigation, weed control and fertilizer ($P<0.0002$) (Table 4.5). When irrigation was not applied, fertilizer increased the ratio above that measured in the other unirrigated treatments. Weed control alone, or the combination of weed control and fertilizer, however, did not alter the ratio from that measured in the control (Table 4.8).

In irrigated pots, both weed control and fertilizer decreased the root to shoot ratio compared to that recorded in pots with only irrigation. The combination of irrigation, weed control and fertilizer, however, did not alter the ratio from that of seedlings subjected to irrigation only.

Table 4.8. Mean root to shoot length ratio for seedlings grown with combinations of irrigation, weed control and fertilizer ($P<0.05$). Different letters indicate treatment differences. $N \geq 6$.

Treatment	Mean Root to Shoot Length Ratio
Control	2.03^b (1.76-2.34)
Weed control	2.21^b (2.05-2.39)
Fertilize	3.01^a (2.64-3.13)
Weed cont+fert	1.95^b (1.61-2.35)
Irrigate	2.66^a (2.42-2.92)
Irr+weed control	1.08^c (0.96-1.23)
Irr+fertilize	1.97^b (1.70-2.27)
Irr,Weed+fertilize	3.01^a (2.84-3.81)

Weed Biomass

Both irrigation ($P<0.0001$) and fertilizer addition ($P<0.005$) significantly influenced weed biomass (Table 4.5). The addition of irrigation alone doubled weed weight, whereas the combination of irrigation and fertilizer resulted in a 3-fold weight increase. The addition of fertilizer without irrigation did not change weed weight from than measured in control pots (Table 4.9).

Table 4.9. Mean weed weight (grams) with combinations of irrigation and fertilizer. Different letters indicate treatment diffeences. N = ≥8.

Treatment	Mean Weed Weight (g)
Control	6.12^{c} (5.50-6.85)
Irrigate	12.71^{b} (11.23-14.38)
Fertilize	7.12^{c} (6.14-8.10)
Irrigate+fertilize	20.92^{a} (18.20-24.04)

Shoot Nutrient Concentrations

Both weed control and fertilizer increased the levels of phosphorus, potassium and iron in shoot material. This had an additive effect when weed control and fertilizer were combined. Shoot material from seedlings grown with a combination of weed control and fertilizer had 6 times the concentration of phosphorus, 8 times the concentration of potassium and 6 times the concentration of iron than did material from pots with only irrigation (Table 4.10).

The concentration of calcium, magnesium and manganese present was greater in shoot material from seedlings grown with fertilizer, weed control or a combination of the two than from those grown with only irrigation, although there was no great difference between the concentration from these 3 treatments.

Sodium levels from seedlings grown with fertilizer and irrigation were approximately half that measured in seedlings grown in other treatments. The percentage sulphur appeared to respond to weed control but not fertilizer, with weed control increasing the level.

Zinc levels were increased by both fertilizer addition (3 fold) and weed control (6 fold). The combination of weed control and fertilizer resulted in 4 times as much zinc as in shoot material from the 'irrigate only' treatment. Weed control increased boron levels by a factor of 4. The addition of fertilizer, however, resulted in a decrease in boron concentrations, although this may not be significant, and is consistent with the dilution effect expected with increased growth.

Concentrations of copper were 3 times lower in shoot material from fertilized treatments than in 'irrigate only', which may be a result of dilution due to increased growth with fertilizer addition. Weed control halved the concentration of copper.

Table 4.10. Shoot nutrient concentrations for the irrigated treatments.

Treatment	%P	%K	%Ca	%Mg	%Na	%S	Zn ppm	B ppm	Fe ppm	Mn ppm	Cu ppm	%N
IWCF*	0.18	0.96	0.93	0.36	0.34	0.19	47.3	33.2	900	422	13.5	2.30
IWC	0.07	0.46	0.89	0.36	0.32	0.18	61.6	42.6	330	413	25.1	-
IF	0.11	0.37	0.85	0.33	0.17	0.13	33.3	7.5	474	410	15.8	-
I	0.03	0.12	0.66	0.25	0.31	0.13	10.2	12.4	152	291	46.6	-

* I = irrigate; IF = irrigate+fertilize; IWC = irrigate+weed control; IWCF = irrigate, weed control and fertilize

Experiment 2. Growth and germination of *E. amygdalina* in sterilized pasture soil and in soil from remnant bushland

Methods

The experiment was established as a completely randomised design in which the germination and growth of *E. amygdalina* was monitored in three soil types. Treatments were replicated 10 times.

Pasture soil was collected in December 1990 from the University farm at Cambridge, and prepared in the manner outlined in Experiment 1 ('control'). After sieving, however, half of the soil was steam sterilized at 70°C for 2 hours prior to placing in pots ('sterilized').

Soil was also collected from a remnant stand of dry sclerophyll woodland located near the Richmond Golf Course (see Appendix 1 for site description), a site approximately 2 km from the University farm, with similar geology, soil type and dominant vegetation. This soil was prepared as per Experiment 1 ('woodland').

Seed was prepared and sown in the manner explained in the previous experiment. All pots were irrigated daily and weeded weekly.

Germination and height growth were monitored in the manner previously described. Harvesting techniques were as per Experiment 1. Plant nutrient levels were determined for the 'control' and 'sterilized' treatments, but not for the 'woodland' treatment. Sterilized and control soils were analysed for nutrient concentrations by the Department of Primary Industries Mt Pleasant Laboratories .

Data were analysed using the General Linear Model procedure in SAS (SAS Institute Inc 1989a, b). Germination data were converted to percentages before being arcsine transformed as recommended by Sokal and Rohlf (1969). Seedling height, root length, root to shoot length ratio and weight data were log transformed to remove heteroscedacity, before analysis of variance.

Results

Germination

Sterilizing the soil significantly reduced the percentage germination ($P<0.03$) (Table 4.14). Germination on woodland soil did not differ from that in the control treatment (Table 4.11, Figure 4.6). Germination rate was slightly slower in both sterilized and woodland soils than in the control soil, as indicated by the greater number of days taken to achieve 90% germination (Table 4.12). This, however, was not statistically significant ($P<0.05$).

Table 4.11. Mean germination percent for control, sterilized and woodland treatments ($P<0.05$). Different letters indicate treatment differences. N = 10.

Treatment	Mean Germination Percent
Control	24.64^{a}
	(20.12-25.27)
Sterilize	14.90^{b}
	(12.21-17.80)
Woodland	21.11^{a}
	(15.34-27.45)

Table 4.12. Rate of germination (days) of *E. amygdalina* in control, sterilized and woodland soils. Different letters in columns indicate treatment differences.

Treatment	Rate of germination (days)		
	t10	*t50*	*t90*
Control	5.0^{a}	11.0^{a}	16.0^{a}
	(2.0-7.0)	(4.0-14.0)	(11.0-20.0)
Sterilized	5.0^{a}	11.5^{a}	20.0^{a}
	(2.0-9.0)	(3.0-14.0)	(12.0-22.0)
Woodland	5.0^{a}	11.0^{a}	21.0^{a}
	(0.5-5.5)	(9.0-12.0)	(12.0-22.0)

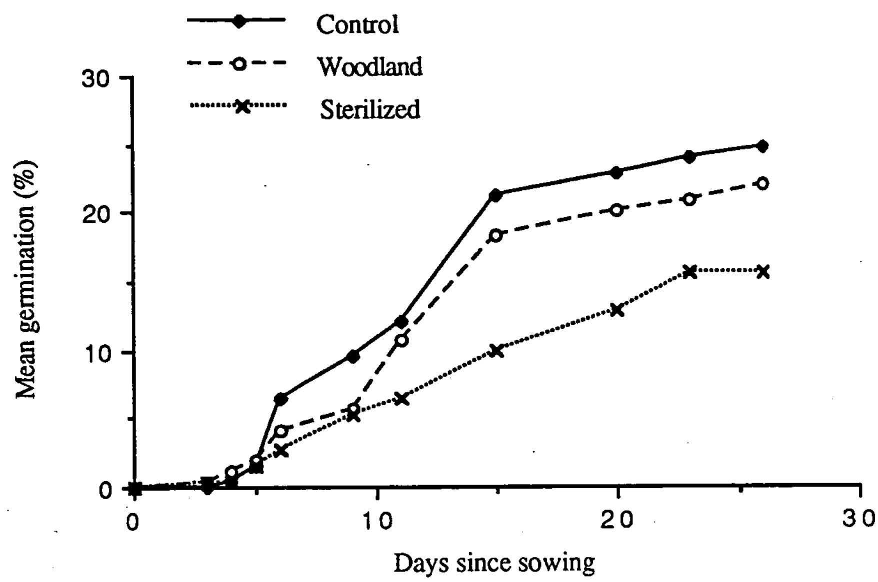

Figure 4.6. Mean germination of *E. amygdalina* in sterilized and woodland soil.

Height

Eucalypt seedling height was greater in the sterilized (P<0.0001) than in the control treatment (Tables 4.13, 4.14, Figure 4.7). The growth rate over time for seedlings in sterilized soil was 2.5 - 3.5 times that of seedlings in the other treatments, approximating the weekly growth rate measured in seedlings grown with irrigation, weed control and fertilizer in the previous experiment, and similar to weekly rates measured for *E. amygdalina* seedlings growing in potting mix (Figure 4.3). The growth of seedlings in sterilized soil approximated the exponential growth which typifies healthy early plant development.

Only in the sterilized treatment was there variation in seedling heights, with height ranging from 0-25 cm. In the other treatments, all seedlings were less than 5 cm high (Figure 4.8).

Table 4.13. Mean seedling height (cm) in control, sterilized and woodland soils (P<0.05). Different letters indicate treatment differences. N = 10.

Treatment	Mean Seedling Height (cm)
Control	3.72[b] (3.57-3.89)
Sterilize	9.88[a] (8.20-11.92)
Woodland	2.90[c] (2.70-3.11)

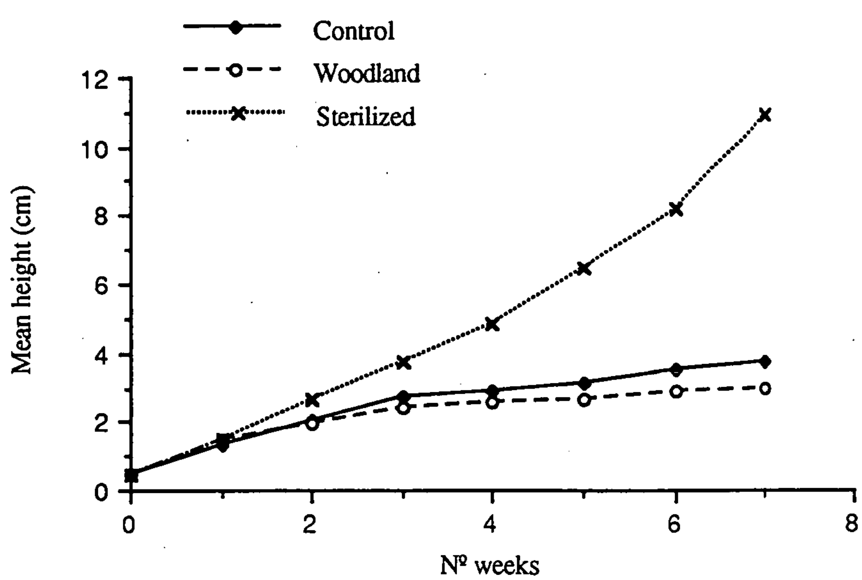

Figure 4.7. Mean height of seedlings growing in control, sterilized and woodland soil

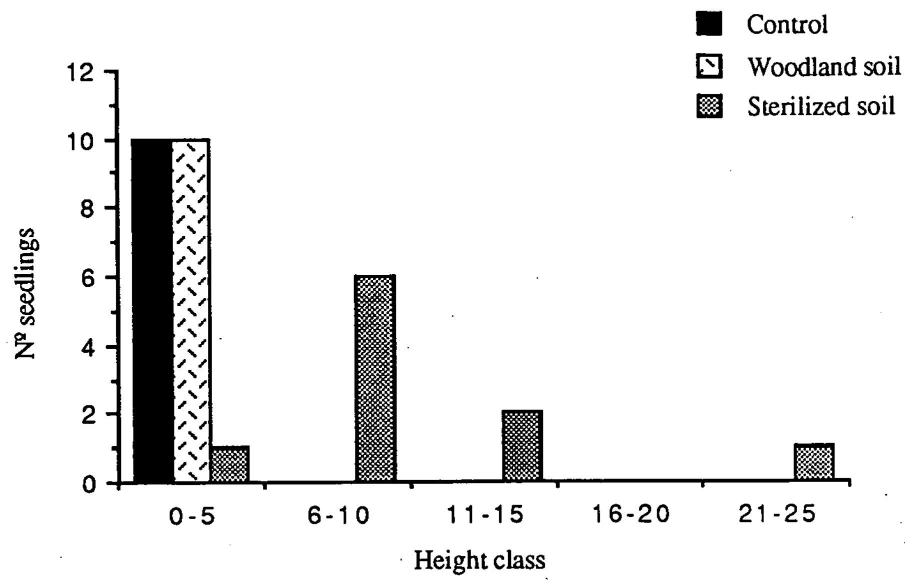

Figure 4.8. Variation in height distribution of seedlings growing in control, sterilized and woodland soil

Table 4.14. ANOVA table of the effects of soil treatment on establishment.

Source of Variation	DF	MS	F	p
(a) Germination				
Control	1	0.109	4.63	0.0348
Woodland	1	0.0069	0.53	0.4720
Sterilized	1	0.0700	5.36	0.0285
RESIDUAL	27	0.0130		
(b) Height				
Control	1	1.461	7.3	0.0087
Woodland	1	0.3108	3.47	0.0733
Sterilized	1	4.7534	53.11	0.0001
RESIDUAL	27	0.0895		
(c) Weight				
Control	1	3.675	2.54	0.1163
Woodland	1	28.7653	50.64	0.0001
Sterilized	1	0.2818	0.50	0.4875
RESIDUAL	26	0.5680		
(d) Root Length				
Control	1	0.018	0.11	0.7452
Woodland	1	0.8910	7.43	0.0115
Sterilized	1	0.1770	1.48	0.2356
RESIDUAL	25	0.1198		
(e) Root to Shoot Ratio				
Control	1	0.015	0.07	0.7962
Woodland	1	4.4119	18.13	0.0003
Sterilized	1	1.0012	4.11	0.0533
RESIDUAL	25	0.2434		

Eucalypt Biomass

Mean eucalypt weight was significantly lower in the woodland soil than in the other two treatments ($P<0.0001$) (Table 4.14). The weight of seedlings growing in control and sterilized soils was not significantly different, even though the height of seedlings in sterilized soil was three times as great as the height in control treatments (Table 4.15).

Table 4.15. Total mean biomass (grams) of seedlings grown in control, sterilized or woodland soil ($P<0.05$). Different letters indicate treatment differences. $N \geq 8$.

Treatment	Mean Seedling Weight (gm)
Control	0.49^a (0.36-1.12)
Sterilize	0.38^a (0.28-0.53)
Woodland	0.04^b (0.03-0.05)

Root Length

Mean root length was less for seedlings grown in woodland soil than in the control or sterilized treatments ($P<0.01$) (Table 4.14). There was no difference in root length of seedlings grown in sterilized and control treatments (Table 4.16).

Table 4.16. Mean root length (cm) of seedlings grown in control, sterilized or woodland soil ($P<0.05$). Different letters indicate treatment differences. $N \geq 8$.

Treatment	Mean Root Length (cm)
Control	17.61^a (14.89-20.82)
Sterilize	21.49^a (19.14-24.14)
Woodland	11.25^b (9.72-13.81)

Root to Shoot Length Ratio

Seedlings grown in woodland soil had a greater root to shoot length ratio than did those in control pots ($P<0.0003$). Similarly, sterilizing the soil increased the ratio from that measured in the control treatment (Table 4.17). The mean root to shoot length ratio in sterilized soil was less than that in woodland soil (Table 4.17).

Table 4.17. Mean root to shoot ratio of seedlings grown in control, woodland and sterilized soil ($P<0.05$). Different letters indicate treatment differences. $N \geq 8$.

Treatment	Mean Root to Shoot Length Ratio
Control	1.08^{c} (0.89-1.32)
Sterilize	1.74^{b} (1.41-2.15)
Woodland	2.94^{a} (2.41-3.59)

Shoot Nutrient Concentration

There was approximately twice as much phosphorus, potassium and manganese in shoot material from seedlings grown in sterilized soil than in the control. The concentrations of calcium, magnesium, sodium, sulphur and zinc did not differ between treatments. There was 3 - 5 times less boron, 3 times less iron and half as much copper in seedlings growing in sterilized soil than in the control, which can probably be related to a dilution effect resulting from the increased growth of seedlings in sterilized soil (Table 4.18).

Table 4.18. Shoot nutrient concentrations in sterilized and control shoot material.

Treatment	%P	%K	%Ca	%Mg	%Na	%S	Zn ppm	B ppm	Fe ppm	Mn ppm	Cu ppm	%N
Sterilized	0.16	0.98	0.98	0.38	0.25	0.20	60.1	12.1	101	835	14.4	3.00
Control	0.07	0.46	0.89	0.36	0.33	0.18	61.6	42.6	330	403	25.1	-

Soil Nutrient Concentration

The soil concentrations of five macronutrients in sterilized and unsterilized soil are presented in Table 4.19. There was 20% more nitrogen, 10% more phosphorus; 9% more potassium and 8% more magnesium in sterilized than in unsterilized soil. There were no differences in the calcium concentration. Total nutrient concentrations, however, only give a general indication of the soil nutrient status. Details of available concentrations, and of the form of nutrients, would have been more useful, but were beyond the scope of this project.

Table 4.19. Concentration of nutrients in sterilized and unsterilized soil.

Treatment	Total N (%)	Total P (ppm)	Total K (ppm)	Ca (ppm)	Mg (ppm)
Sterilized	0.150	257	775	1250	1125
Control	0.119	222	700	1250	1025

Summary of Results

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* Irrigation increased *E. amygdalina* seed germination, whereas fertilizer application decreased it (Table 4.1).
* Weed control in the absence of irrigation also resulted in reduced germination (Table 4.1), as did soil sterilization (Table 4.11).
* Final seedling height was slightly increased by irrigation, or a combination of irrigation and fertilizer, but only the combination of irrigation,weed control and fertilizer (Table 4.3), or soil sterilization at 70°C (Table 4.13), resulted in height growth approximating that recorded in potting mix. As well, height variation was only apparent in these two treatments (Figures 4.5, 4.8).
* Root length was increased by fertilizer addition, both with and without irrigation, and by the combinations of irrigation and weed control or weed control and fertilizer (Table 4.7). Mean root length was less when seedlings were grown in woodland soil (Table 4.16).
* Irrigation increased the root to shoot length ratio of *E. amygdalina* seedlings grown with no treatment or with the combination of weed control and fertilizer. The root to shoot ratio of seedlings grown with weed control or fertilizer alone, however, was less with irrigation than without (Table 4.8). In the absence of irrigation, fertilizer addition increased the root to shoot ratio, but when irrigation was applied, the ratio was decreased by fertilizer addition. Greater root to shoot ratios were also measured in sterilized and woodland soil than in the control (Table 4.17).
* The combination of weed control and fertilizer increased seedling weight above that of the control, when irrigation was applied (Table 4.6). Seedling weight was less in woodland soil than in the control treatment (Table 4.15).
* Weed biomass was increased by both irrigation and the combination of irrigation and fertilizer (Table 4.9).
* Shoot nutrient concentrations measured in sterilized soils or with the combination of irrigation, weed control and fertilizer suggest that the growth response in these treatments may have been related to increased nutrient uptake. Nutrients which may have been important are potassium, phosphorus or copper (Tables 4.10, 4.18).

Discussion

Irrigation

Irrigation more than doubled germination percent in most treatment combinations studied (Table 4.1), but did not significantly influence germination rate (Table 4.2). Likewise, in the field experiment outlined in Chapter 3, percentage emergence was significantly increased with irrigation, albeit slightly, while the rate of emergence was unaffected. In both field and glasshouse situations, germination is most likely to occur on those sites with a favourable soil moisture level. Irrigation is likely to increase the number of such sites (Harper 1977), which, while increasing overall percentage germination, may mean that germination rate is unaffected.

The mean height of *E. amygdalina* seedlings grown with irrigation was approximately 30% greater than the height of seedlings in unirrigated pots (Table 4.3). In combination with weed control and fertilizer, irrigation resulted in a 60% increase in mean seedling height. This suggests that when seedlings of this species are growing 'normally' (ie exhibiting exponential growth), irrigation can substantially increase growth.

Weed control

Without irrigation, weed control decreased germination of *E. amygdalina*, whereas when irrigation was applied, the germination percent was unaffected by weed control (Table 4.1). In the previous field experiment, it was found that long term weed control resulted in less emergence than did initial weed control, which may have been related to the method of weed control. In the present experiment, this result may be associated with soil disturbance during hand weeding, and consequent loss of soil seed contact.

Weed control had no effect on the height of seedlings unless fertilizer was also applied (Table 4.3), which suggests that nutrient competition was more important than moisture competition in causing seedling growth check in *E. amygdalina*. Ellis *et al.* (1985) similarly found that competition for nutrients contributed to the growth inhibition of *Eucalyptus delegatensis* seedlings. The importance of weed control for establishment was also highlighted in the broadacre and Cambridge field experiments.

Fertilizer addition

There is disagreement among authors as to the effect of fertilizer on seed germination. Weatherly (1985) coated seed of a range of native species in nutrient powder, and recorded greater germination capacity. Lockett (1978), on the other hand, found in glasshouse experiments that fertilizer application had a significant and detrimental effect on the germination capacity of *Eucalyptus obliqua*, although in the field no positive or negative effects were measured. Such detrimental effects may have been due to altered pH with fertilizer addition, or to increased osmotic stress. In the field experiment detailed in Chapter 3, fertilizer addition at sowing time had no consistent effect on percentage emergence. In the present experiments, however, germination of *E. amygdalina* was significantly and substantially reduced by fertilizer addition (Table 4.1), although the rate of fertilizer application was approximately half of that applied in the field. A number of reasons for the discrepancy between field and glasshouse results are possible. It may be that fertilizer applied in the field was leached from the surface soil before germination commenced, and was therefore unavailable to germinating seedlings. In the glasshouse, germination was more rapid than in the field, and such a leaching process may not have occurred before the onset of germination. In the field, it may also be that factors other than fertilizer addition were more significant in determining percentage emergence.

The result could be related to a difference in the composition of the fertilizers used. The fertilizer used in the glasshouse experiments had almost twice as much nitrogen as that used in the field, although the concentration of other nutrients was similar. Croft and Venning (1985), however, found that increased levels of nitrogen promoted germination in a range of native species, while increased levels of phosphorus decreased it, although responses to fertilizer application are likely to be species specific.

The discrepancy between field and glasshouse results suggests that despite the negative results recorded in the glasshouse, applying fertilizer in the field at the time of sowing may have no detrimental effect on germination, although the benefits of applying fertilizer at this time are questionable.

Fertilizer addition has generally been found to increase the height of eucalypt seedlings grown in both field and glasshouse experiments (Moore and Keraitis 1971; McIntyre and Pryor 1974; Lamb 1977; Cromer and Williams 1982; Ellis *et al.* 1985; Ward *et al.* 1985; Schonau and Herbert 1989). In these glasshouse experiments, however, only the combination of weed control and fertilizer substantially increased mean height, suggesting competition for nutrients as a factor influencing growth (Table 4.3). Although fertilizer addition did not increase height in unirrigated pots, both root length and the root to shoot ratio were increased. Similar results have been reported by Lahiri (1980) and Schonau and Herbert (1989). Lahiri (1980) suggests that fertilizer addition may be important at sites where periodic drought is common, because the increased root growth in response to fertilizer, and the resultant deeper root penetration, may increase survival.

Phosphorus was the only nutrient with a greater concentration in fertilized than in other treatments (Table 4.10), although the nitrogen concentration is unknown but might be expected to increase with fertilizer application. Where increases were recorded for other nutrients, they were generally present in both weed control and fertilizer treatments. This may suggest that phosphorus was deficient in the soil, and indeed, the concentration of phosphorus was found to be only 222 parts per million, a level considered by Russell (1986) to be capable of causing plant nutrient deficiencies.

Although the shoot nitrogen content is not known for most treatments, the nitrogen to phosphorus ratio in shoot material from treatments with irrigation, weed control plus fertilizer, or sterilized soil, was close to 15:1, which is the ratio considered by Cromer *et al.* (1981) to be optimal for some eucalypt species. Although the relative concentrations of nitrate-N and ammonium-N are not known, soil sterilization slightly increased the total soil nitrogen content, as probably did fertilizer addition, which may suggest that nitrogen was limiting in other treatments. Ellis *et al.* (1985) recorded a positive response in *E. delegatensis* to additions of nitrogen, and concluded that growth check in this species at some sites was a result of low soil nitrification and competition for nitrogen from grass and associated vegetation. In earlier work, Ellis (1974) found that some agricultural soils had a reduced rate of nitrogen mineralization, and suggested that forest trees grown on such soils can be expected to suffer a degree of nitrogen deficiency. Suppression of nitrification under grassland is also discussed by Purchase (1974).

Many authors have investigated critical nutrient concentrations in plants. In eucalypts, nutrient concentrations have been found to differ with species, age of plant tissue, and the type of tissue tested (Schonau and Herbert 1989). Sampling only shoot material may, therefore, not provide appropriate information on nutrient concentrations. Foliar concentrations of nitrogen, phosphorus and potassium in some eucalypt species have been found to fall in the range of 1.2 - 1.8% (N), 0.07 - 0.26% (P), and 0.2 - 1.6% (K) (Bell and Ward 1984; Olsen and Bell 1990). Ellis *et al.* (1985) found that concentrations of these nutrients in *E. delegatensis* foliage varied with weed control treatment. They measured concentrations of 0.63 (N), 1.50 (P) and 0.50% (K) in unweeded plots; 1.50 (N), 0.19 (P) and 0.40% (K) in herbicide treated plots; and 1.20 (N), 1.50 (P) and 0.63% (K) with manual weeding.

Critical concentrations of copper, boron, zinc and iron in eucalypts have been measured in the range 6 - 17 ppm, 46 - 100 ppm, 10 - 18 ppm, and > 140 ppm respectively (Schonau and Herbert 1989). From the nutrient concentrations and growth responses measured in *E. amygdalina*, the only one of these which may have influenced growth was copper, although there is no real evidence of copper toxicity.

Soil sterilizing

Soil sterilizing significantly reduced mean germination percent (Table 4.11). It was observed that sterilized soil was more prone to waterlogging than unsterilized soil, which may have been related to an alteration in soil structure. Fungal attack was not recorded in any pot, and it may be that the oxygen supply was restricted in waterlogged soils, thereby reducing germination. Florence and Crocker (1962) suggested that gamma irradiation was a more appropriate method of sterilization than heat treatment, as soil structure is not affected.

Sterilizing the soil resulted in a significantly greater mean seedling height than in the control treatment (Table 4.13). Warcup (1981) describes a similar response in *Eucalyptus regnans* grown in soil sterilized at 60° or 70°C. Analysis of the shoots of *E. amygdalina* seedlings grown in sterilized soil indicated increased levels of phosphorus and potassium, which is also consistent with the results outlined by Warcup (1981) for *E. regnans*. Warcup (1981) was unclear whether this result was related to increased chemical availability or to increased mycorrhizal uptake resulting from the sterilizing process.

Florence and Crocker (1962) found that heat sterilizing increased the shoot growth of *Eucalyptus pilularis* seedlings. The addition of complete fertilizer gave a comparable increase in mean leaf area per pot, although seedlings remained unhealthy. Sterilization for 48 hours at 70°C increased dry weight by a factor of three, and the combination of sterilizing and nitrogen plus phosphorus addition increased dry weight approximately 7 times. They attributed the response to heat sterilizing in part to the promotion of soil nitrification, which increased the concentration of nitrogen available for seedlings, thereby promoting growth. The response to heat sterilizing differed with the temperature of sterilization. Interestingly, heating soil at 60°C for 30 minutes is considered adequate to stimulate growth in commercial nurseries (Warcup 1981), although such growth promotion is not necessarily related to alterations in soil microflora (Wilhelm 1966).

After studies in which soil was sterilized with gamma rays rather than heat, Florence and Crocker (1962) concluded that soil micro-organism antagonism may have a significant influence on *E. pilularis* growth. It was later concluded that this growth inhibition was a result of a toxin produced by a strain of *Cylindrocarpon destructens*, a micro-organism found on the roots of *E. pilularis* seedlings (Evans *et al.* 1967). Ashton and Willis (1982) related the same species to poor survival of *E. regnans* seedlings grown in *E. regnans* forest soil. Similar species have been associated with crown dieback in *Eucalyptus obliqua* and *Eucalyptus delegatensis* in Tasmania (Warcup 1981).

Renbuss (1968) also concluded that seedling growth stimulation was at least partly a result of altered soil microflora. Attiwill and Leeper (1987) suggest that sterilizing initiates a new succession of soil micro-organisms which may markedly affect growth. In agreement with this, Renbuss (1968) measured a rapid recolonization of sterilized soil by many species of micro-organisms not found in untreated soil. She measured much greater numbers of micro-organisms shortly after soil treatment, a phenomenon apparently common after soil sterilization (Ahlgren 1974). The length of time taken for the heat-induced microflora to revert to its pre-treatment state was almost a year, which coincided with the period for which seedling growth stimulation was measured (Renbuss 1968).

Warcup (1981) found that seedlings growing in heat sterilized soil had fewer types of mycorrhizas on their roots than did seedlings in untreated soil, with the most abundant mycorrhizal fungi being ascomycetes. He indicated that several of these ascomycetes have also been isolated from the roots of eucalypt seedlings growing after fires in many parts of Australia.

Similar increases in eucalypt seedling growth have also been reported following high intensity fire, or localized pockets of high intensity burning, which create an ash bed effect (Orme 1971; Fagg 1981; Geard 1987). Seedling response to the 'ash bed' is believed to be related to alterations in soil chemistry leading to an increased availability of soil nutrients, changed pH (Renbuss 1968; Ellis *et al.* 1982; Ellis and Graley 1983; Humphreys and Craig 1981), and destruction of competing vegetation and allelochemes (Humphreys and Craig 1981), as well as to alterations in soil microflora resulting from heat sterilization.

Woodland soil

Ellis *et al.* (1985) found that inhibition of *E. delegatensis* seedling growth could be overcome by mixing inhibitory soil with soil from a healthy forest stand. In the Cambridge area, healthy forests are non-existent due to widespread dieback, and soil was therefore collected from an 'unimproved' patch of dry sclerophyll woodland. This soil, however, proved to be at least as inhibitory to seedlings as pasture soil. While seed germination was not affected in woodland soil, seedling height, weight and root length were considerably lower than in the control treatment(Tables 4.13, 4.15, 4.16). This was probably not related to the root-rot fungus, *Phytopthora cinnamomi*, as healthy *Banksia marginata*, a species susceptible to this fungus, were present at the collection site. It is possible that growth was inhibited by similar processes in both pasture and woodland soil, which may be related to soil fertility or microflora. Florence and Crocker (1962) overcame growth inhibition of *E. pilularis* seedlings grown in soil from *E. pilularis* forest by sterilization, which in a natural situation would be provided by fire.

Dry sclerophyll forest and woodland communities are adapted to fire (Christensen *et al.* 1981), and in many instances fire is a prerequisite of seedling establishment. Therefore, the inhibition of *E. amygdalina* seedlings grown in soil collected from residual dry sclerophyll woodland may be overcome by heat treatment of the soil or by fire.

Conclusions

The experiments have clearly demonstrated a very strong growth check in *E. amygdalina* seedlings grown in pasture or dry sclerophyll woodland soil, which could only be overcome in pasture soil by heat treatment or the addition of a combination of weed control and fertilizer. In inhibited seedlings, growth was very stunted, and there was little variability in the range of seedling heights. There was little response to irrigation in these seedlings, suggesting that factors other than moisture availability were responsible for growth inhibition. In contrast, unchecked seedlings responded vigorously to irrigation, and during the 7 weeks of the experiment, growth of these seedlings was actually faster than that of seedlings grown in potting mix.

Weed control alone did not overcome seedling growth inhibition, although there was an increase in nutrient concentrations in shoot material where weed control was applied. This may be related to the increased root growth measured with weed control. Fertilizer alone, while slightly increasing seedling height, also did not overcome growth check. That growth check was overcome by a combination of weed control and fertilizer addition suggests that competition for nutrients was at least partly responsible for the growth inhibition of seedlings observed in the other treatments. Seedlings in pots with weed control and fertilizer or in sterilized soil had significantly greater concentrations of phosphorus and potassium in shoot material, suggesting that these nutrients may have contributed to growth check in the other treatments.

While it is likely that a nutrient imbalance is a cause of *E. amygdalina* seedling growth check, the mechanisms are unclear. Low rates of soil nitrogen mineralization are possible, which may influence growth, and an imbalance in phosphorus, potassium or copper may play a role. The presence of antagonistic soil microflora cannot be discounted. It would seem that the processes operating are complex, and further research is required to develop a greater understanding of eucalypt growth check on pasture and dry sclerophyll woodland sites in the Midlands.

CHAPTER 5. The effect of inter- and intra-specific competition on establishment.

Introduction

Weed competition for moisture (Sands and Nambiar 1984) and nutrients (Ellis *et al.* 1985) has been demonstrated in many instances to decrease tree seedling growth. Despite the abundance of information on the general effects of competition on tree seedling growth, there have been relatively few studies discriminating the effects of competition from different weed types. Webb *et al.* (1983) grew *E. delegatensis* seedlings alone, in monoculture, or with a seedling of the grass *Poa labillardieri*, recording a significant decrease in *E. delegatensis* growth when there was competition from a grass or another eucalypt seedling. Gordon *et al.* (1989) were interested in the relative effect of a grass and a forb on the growth of *Quercus douglasii*. They found that competition from the grass species resulted in greater shoot suppression and mortality in *Q. douglasii* than did competition from the broadleaf species.

When establishing tree and shrub plantations in a pasture environment, tree seedlings may be exposed to competition from grass and broadleaf exotic species, and from other tree seedlings. An understanding of the competitive interactions of such species may therefore assist in developing establishment prescriptions. It was determined in earlier experimental work that competition from exotic weed species affected eucalypt seedling growth, and that, in *E. amygdalina* at least, this was probably related more to competition for nutrients than for moisture, but the effect of particular weed species on eucalypts, and the responses of eucalypt seedlings to this competition, is not known. The aim of the following experiment was to determine the effects of both inter- and intra-specific competition on a range of growth parameters of *Eucalyptus amygdalina* (a tree), *Acacia mearnsii* (a small tree or shrub), *Lolium perenne* (a grass) and *Leontodon taraxacoides* (a forb). A factorial experiment was established, in which the effects of, and responses to, competition were examined. By investigating competitive effects at both high and low soil moisture levels, it was hoped to determine whether competitive effects were related to competition for moisture, or to other factors such as nutrient comeptition.

The species

E. amygdalina (black peppermint) is a widely distributed endemic Tasmanian species, which occurs as a tree in dry sclerophyll forest, grassy forest, sclerophyll shrub woodland and grassy woodland, and as a shrub in open scrub and heath (Kirkpatrick and Backhouse 1981). Because of its wide distribution and common occurrence, it is a species which has regularly been planted on pasture sites. It is likely to be used in the

Midlands in future direct seeding programs, as seed is relatively abundant and the range of sites on which the species is likely to be successful is high.

A. mearnsii, or black wattle, occurs as an understorey shrub or small tree in grassy woodlands, on fertile well drained soils in the driest parts of the state (Kirkpatrick and Backhouse 1981). It is common in the Midlands, and, like *E. amygdalina*, is likely to be a popular species for direct seeding. It is a species with the capacity to fix nitrogen.

L. perenne (perennial rye grass) is a perennial exotic grass which is a common and vigorous component of improved pastures in the Midlands. It has a fibrous root system. Being one of the main grass species likely to compete with tree and shrub species direct-sown on exotic pasture sites, its competitive effects and responses are of interest.

L. taraxacoides, or hawkbit, is common throughout Tasmania, in turf, pasture, waste areas and occasionally in crops (Hyde-Wyatt and Morris 1975). It is a broadleaf species similar in appearance to the dandelion (*Taraxacum officinale*), and has a tap root rather than a fibrous rooting system. Because of its common occurrence, it was included in the experiment.

Methods

E. amygdalina seed, of the same mix described in the previous chapter, was germinated on commercial potting mix and grown to the 2 leaf stage. Commercially available *L. perenne* seed was germinated in a similar manner. To obtain seedlings of the broadleaf species *L. taraxacoides*, field soil from the University farm at Cambridge (Appendix 1) was placed in seed trays in a glasshouse. *L. taraxacoides* is a common species at the Cambridge site, and germination of this species was prolific in the collected soil. Seedlings were also grown to the 2 leaf pair stage. *Acacia mearnsii* seed was heat treated by covering with boiling water and allowing the water to cool before sowing the seed onto commercial potting mix. Seedlings were grown until the first non-cotyledonous leaves emerged. When transplanted, seedlings of approximately 0.5 cm height were chosen for all species.

The study was established as a factorial experiment with a completely randomised design, with two irrigation treatments (+, -) and 6 replicates of each treatment combination. 15 x 20 cm plastic pots were filled with soil collected in January 1991 from the University farm at Cambridge. The soil was sieved to remove organic particles and rocks with a diameter greater than 0.5 cm. Each pot was allocated one target species and one competitor. *E. amygdalina* (target species) was grown alone, in monoculture, or with a seedling of the species *A. mearnsii*, *L. perenne* or *L. taraxacoides*. *A. mearnsii* (target species) was grown alone, in monoculture, or with an *E. amygdalina* seedling.

Likewise, *L. perenne* and *L. taraxacoides* (target species) were grown alone, in monoculture, or in competition with *E. amygdalina.*

When seedlings were grown alone, they were planted in the centre of each pot. When they were grown with another seedling, they were planted approximately 10 cm apart, and 2.5 cm from the pot lip.

Pots were placed into a shadehouse, where seedlings were grown for 8 weeks before being moved to a glasshouse. Average weekly maximum and minimum air temperatures in the shadehouse were 27°C and 8°C respectively. In the glasshouse, temperatures ranged from an average maximum of 32°C to an average minimum of 12°C.

In both the shadehouse and glasshouse, pots were randomly placed to account for any edge effects or differences in light or carbon dioxide concentrations.

Half of the pots in each treatment were irrigated daily to simulate a high level of soil moisture, while the remainder were given approximately 2 litres of water once a week, to simulate a low soil moisture level. All pots were hand weeded weekly.

The height of eucalypt and acacia seedlings was measured weekly until harvesting after 24 weeks. At the time of harvesting, the soil was gently washed from the roots. Length of the longest root and shoot height were measured for *E. amygdalina* and *A. mearnsii* seedlings. It was difficult to measure these parameters in a meaningful manner for *L. perenne* and *L. taraxacoides. A. mearnsii* roots were checked for the presence or absence of rhizobial nodules. All plant material was oven-dried at 60°C until weights were constant (12 hours), after which final root and shoot weight were measured, and the root to shoot length ratio estimated for *E. amygdalina* and *A. mearnsii.*

The effects of intraspecific competition were determined by comparing the final size of seedlings grown alone to that of seedlings in monoculture. Interspecific competition was measured by comparing the final size of seedlings in monoculture with that of seedlings grown alone or in competition with *A. mearnsii, L. taraxacoides* or *L. perenne.*

Residual analysis indicated heteroscedacity, and all data were log transformed to overcome this. The General Linear Model procedure in SAS was then used for analysis of variance (SAS Institute Inc 1989a, b).

Results

<u>Root and Shoot Length</u>

Irrigation significantly influenced *E. amygdalina* seedling height ($P<0.02$) and root to shoot length ratio ($P<0.02$), but did not influence *A. mearnsii* root or shoot length (Table 5.8). Competition influenced *E. amygdalina* height ($P<0.04$) (Tables 5.8, 5.10).

Irrigation

Between-irrigation treatment differences were apparent for both root and shoot length. When eucalypt or acacia seedlings were grown alone, irrigation did not alter mean height or root length (Tables 5.1, 5.2, Figures 5.1, 5.2). Irrigation increased the mean height of eucalypt or acacia seedlings grown with intraspecific competition (Table 5.1, Figures 5.1, 5.2)). Root length of seedlings grown with inter- or intraspecific competition was neither increased nor decreased by irrigation, except when acacia seedlings were grown in competition with *E. amygdalina*, which resulted in a 34% increase in the mean root length of acacias in irrigated pots (Table 5.2).

Intraspecific Competition

Intraspecific competition resulted in significantly greater height of *E. amygdalina* seedlings grown in irrigated pots, but had no effect on height if water was not applied (Table 5.1, Figure 5.1). Root length was greater in unirrigated pots with this form of competition, but the root to shoot length ratio was unaffected (Tables 5.2, 5.3). Intraspecific competition increased the variation in *E. amygdalina* heights (Figures 5.7, 5.8).

Similarly, intraspecific competition increased the mean height of *A. mearnsii* seedlings grown in irrigated pots (Table 5.1, Figure 5.2). *A. mearnsii* root length was also significantly increased by this form of competition in irrigated pots (Table 5.2). While the root to shoot length ratio of *A. mearnsii* was unchanged in irrigated pots, it was significantly increased by intraspecific competition when grown without water addition (Table 5.3)

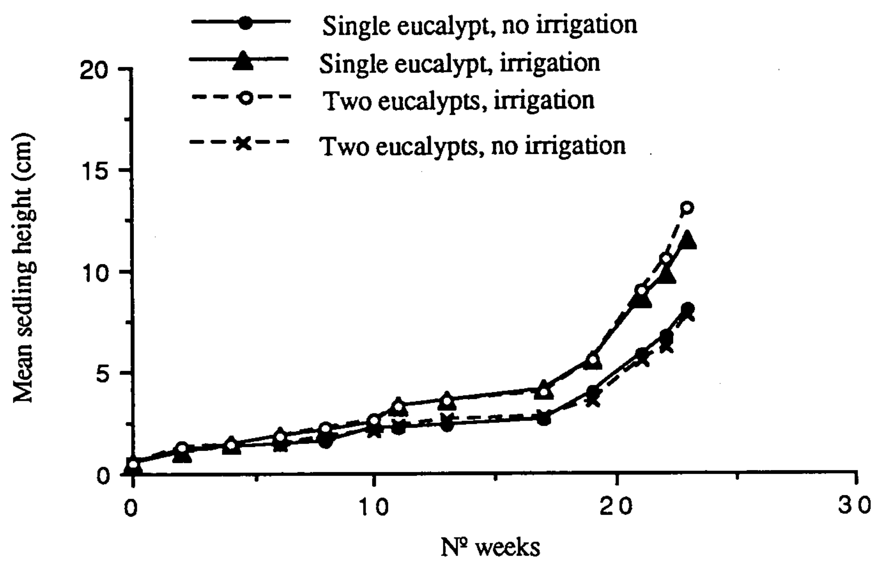

Figure 5.1. Mean height (cm) of eucalypt seedlings grown with intraspecific competition

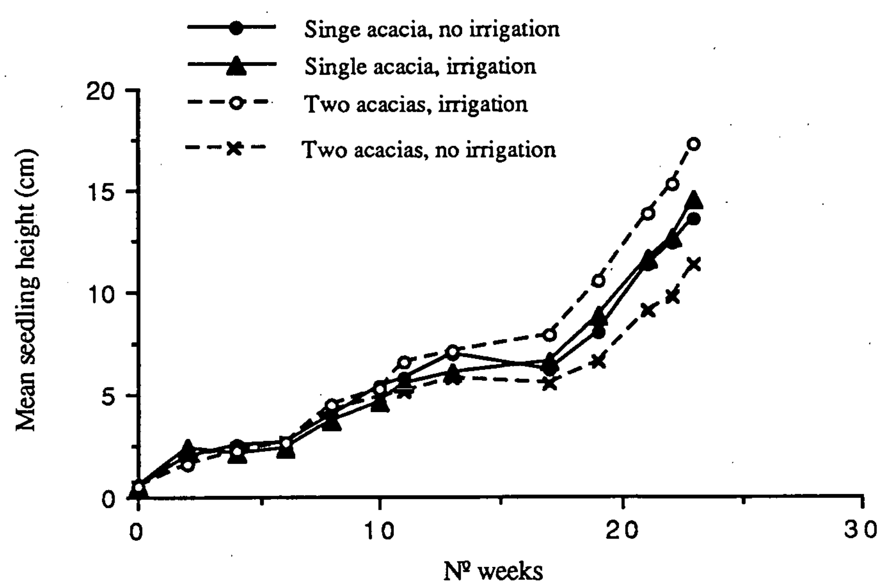

Figure 5.2. Mean height (cm) of acacia seedlings grown with intraspecific competition

The height of *E. amygdalina* seedlings was significantly less, both with and without irrigation, with competition from *L. perenne* (Table 5.1, Figure 5.3) or *L. taraxacoides* (Figure 5.4), and in unirrigated pots root length was similarly reduced by competition from these species (Table 5.2). The root to shoot length ratio was unaffected (Table 5.3). Variation in seedling height decreased with competition from *L. perenne* or *L. taraxacoides* (Figures 5.7, 5.8).

Competition from *A. mearnsii* seedlings had no significant effect on *E. amygdalina* height (Table 5.1, Figure 5.5) or root length (Table 5.2).

With irrigation, *A. mearnsii* height was significantly less with competition from *E. amygdalina* than when grown in monoculture (Table 5.1, Figure 5.6). In irrigated pots, mean root length of *A.mearnsii* was greater with competition from an *E. amygdalina* seedling than with competition from another *A. mearnsii* seedling (Table 5.2). *E. amygdalina* competition increased the root to shoot length ratio of *A. mearnsii* when irrigation was applied.

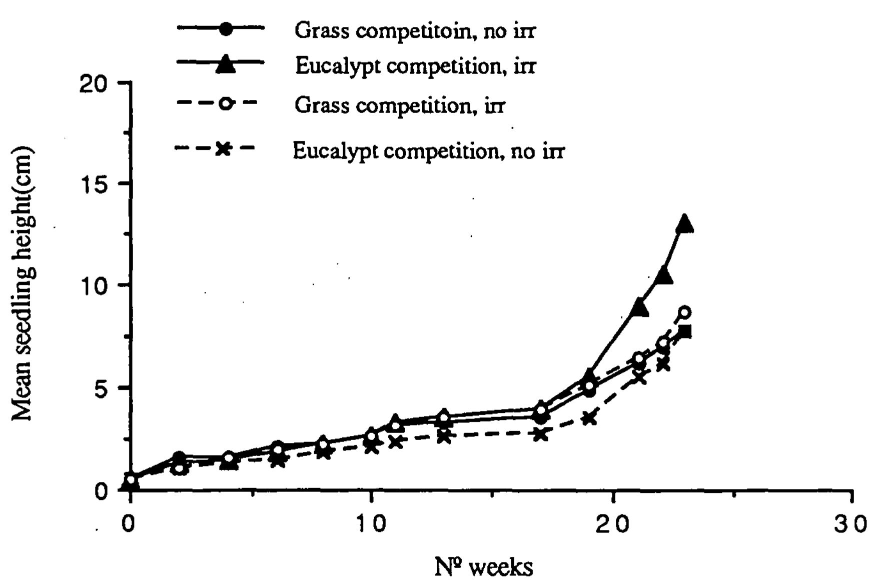

Figure 5.3. Mean height (cm) of eucalypt seedlings grown with competition from *L. perenne*. Irr = irrigation

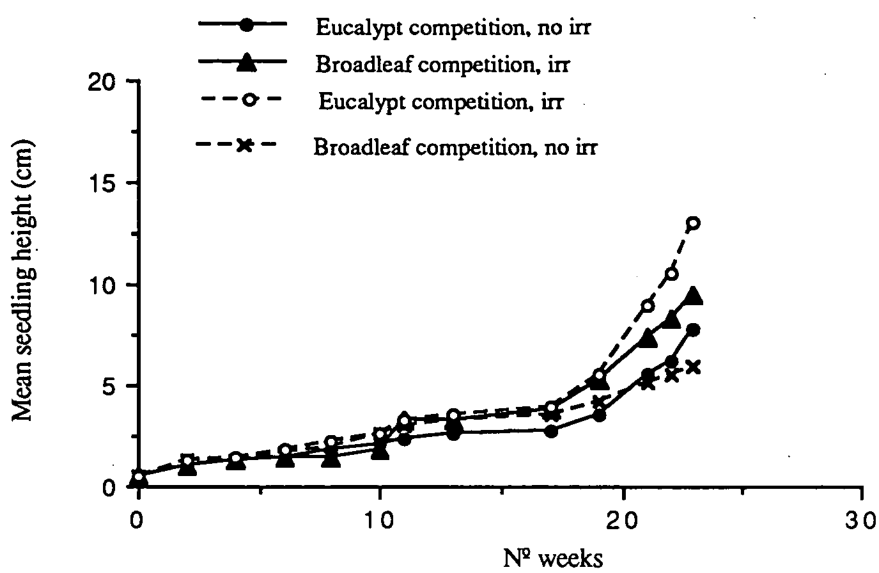

Figure 5.4. Mean height (cm) of eucalypt seedlings grown with competition from *L. taraxacoides*. Irr = irrigated

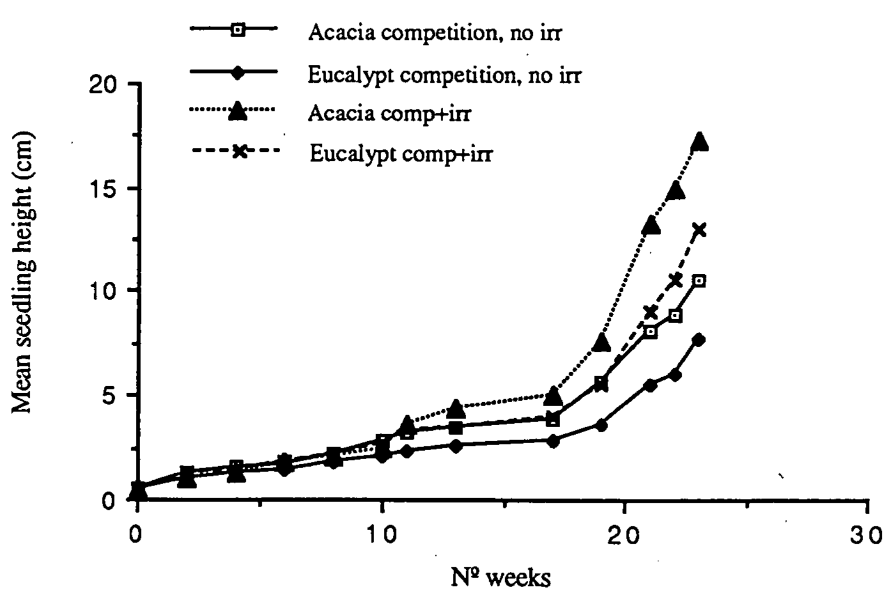

Figure 5.5. Mean height (cm) of eucalypt seedlings grown with competition from *A. mearnsii*. Irr = irrigated

Table 5.1. Mean height (cm) of target species grown with and without competition. Different letters indicate treatment differences (P<0.05).

Target species	Competing species				
	None	*E. amygdalina*	*A. mearnsii*	*L.perenne*	*L.taraxacoides*
(a) irrigated					
E. amygdalina	8.58[c] (7.48-9.84)	12.92[b] (11.25-14.86)	16.32[ab] (13.29-20.04)	8.35[c] (7.28-9.58)	5.77[cd] (4.26-7.81)
A. mearnsii	11.44[bc] (10.09-12.98)	12.65[b] (12.11-13.21)	17.08[a] (15.24-19.15)	-	-
(b)Unirrigated					
E. amygdalina	6.32[cd] (4.88-8.18)	7.86[c] (7.11-8.70)	8.89[c] (7.31-10.83)	5.35[d] (4.27-5.26)	4.76[d] (3.88-5.83)
A. mearnsii	13.00[b] (11.31-14.88)	9.71[bc] (8.09-11.63)	11.49[bc] (10.64-12.43)	-	-

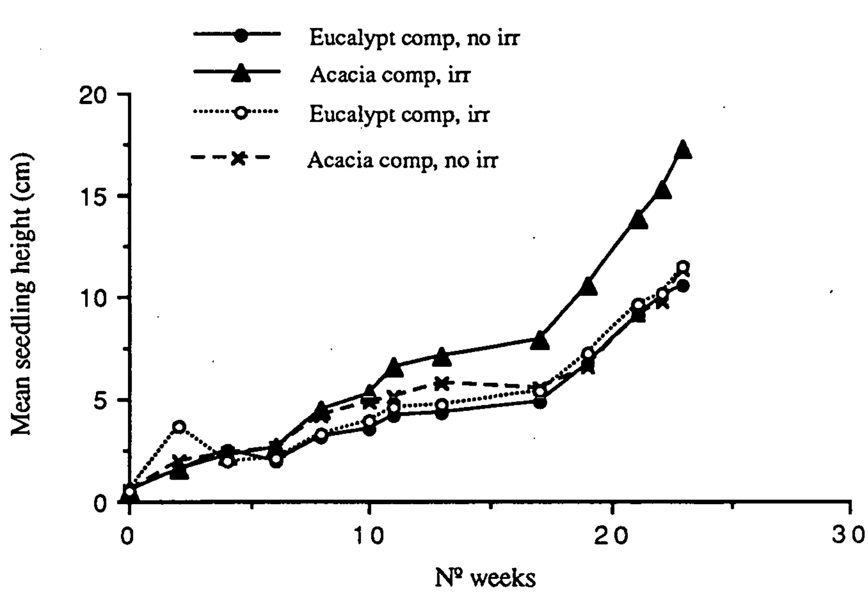

Figure 5.6. Mean height (cm) of acacia seedlings grown with competition from *E. amygdalina*. Irr = irrigated.

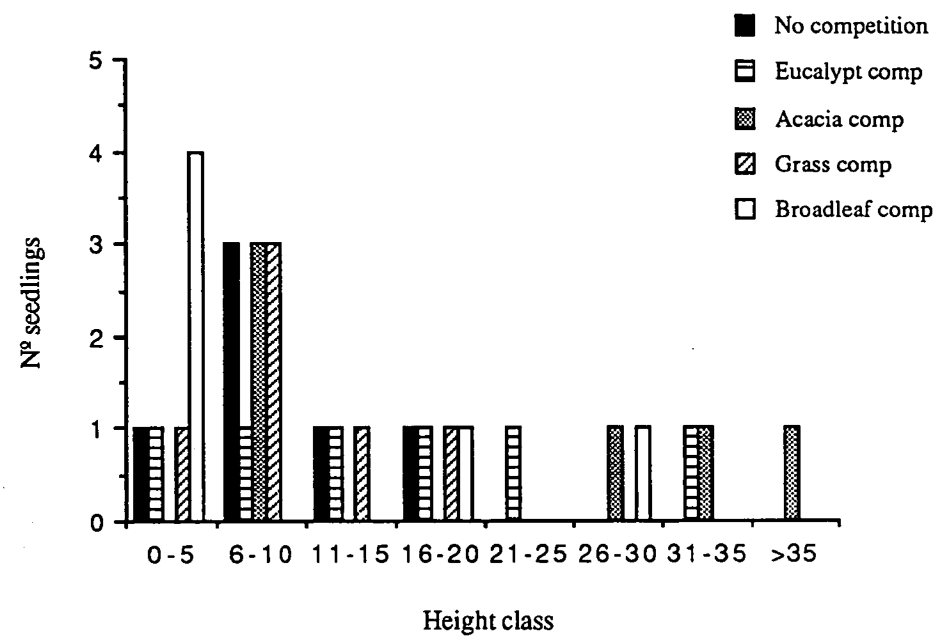

Figure 5.7. Variation in height of eucalypt seedlings grown with irrigation with different neighbour species. Comp = competition.

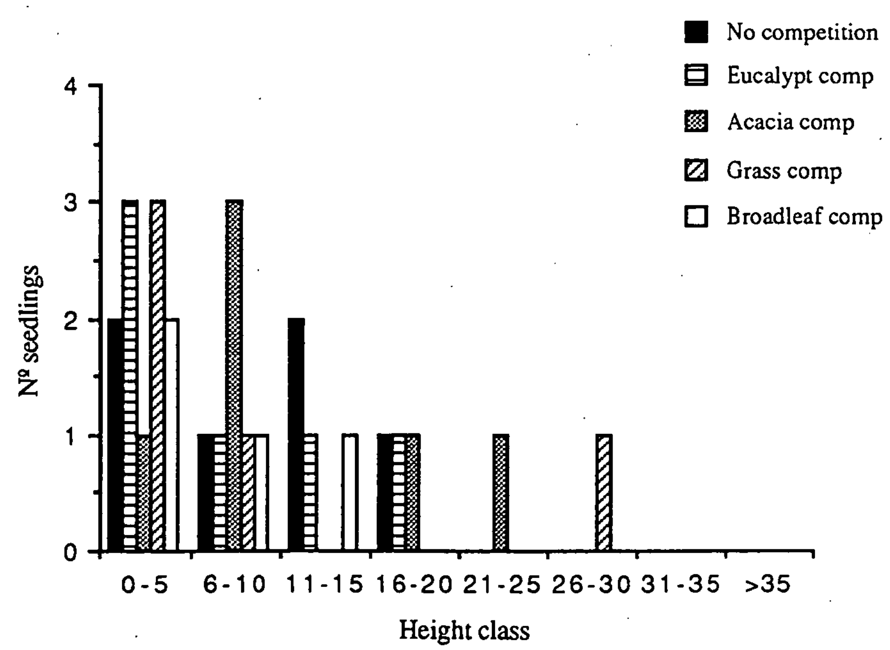

Figure 5.8. Variation in height of eucalypt seedlings grown without irrigation with different neighbour species. Comp = competition.

Table 5.2. Mean root length (cm) of target species grown with and without competition. Different letters indicate treatment differences (P<0.05).

Target species	Competing species				
	None	*E. amygdalina*	*A. mearnsii*	*L.perenne*	*L.taraxacoides*
(a) irrigated					
E. amygdalina	11.34^{e} (9.78-13.15)	13.45^{de} (12.45-14.53)	17.15^{d} (14.48-20.31)	13.79^{de} (7.39-16.25)	12.56^{de} (10.74-14.69)
A. mearnsii	23.27^{cd} (19.32-28.03)	40.61^{a} (36.41-45.28)	32.05^{b} (28.85-35.61)	-	-
(b)Unirrigated					
E. amygdalina	10.68^{e} (8.62-13.23)	14.49^{d} (13.75-15.26)	14.68^{d} (13.16-16.37)	10.59^{e} (8.68-12.93)	11.29^{e} (9.85-12.94)
A. mearnsii	24.93^{c} (22.03-28.19)	26.83^{bc} (22.97-31.34)	30.15^{bc} (28.51-31.88)	-	-

Table 5.3. The root to shoot length ratio of target species grown with and without competition. Different letters indicate treatment differences (P<0.05).

Target species	Competing species				
	None	*E. amygdalina*	*A. mearnsii*	*L.perenne*	*L.taraxacoides*
(a) irrigated					
E. amygdalina	1.44^{cd} (0.85-2.03)	1.04^{cd} (0.92-2.47)	1.22^{d} (1.08-1.37)	1.38^{d} (1.22-1.57)	2.17^{bc} (1.71-2.77)
A. mearnsii	2.41^{abc} (1.76-3.05)	3.21^{a} (2.95-3.48)	1.87^{c} (1.65-2.13)	-	-
(b)Unirrigated					
E. amygdalina	1.69^{cd} (1.47-1.94)	1.84^{c} (1.66-2.05)	1.65^{cd} (1.44-1.88)	1.97^{c} (1.71-2.29)	2.44^{bc} (2.16-2.75)
A. mearnsii	1.92^{c} (1.77-2.07)	3.25^{abc} (1.44-5.06)	2.62^{b} (2.40-2.86)	-	-

Biomass

E. amygdalina total weight was significantly influenced by irrigation ($P<0.05$) and competition ($P<0.05$), and shoot weight was influenced by irrigation (P,0.02) (Table 5.8). Shoot weight and total weight of *L. perenne* were significantly influenced by irrigation (Table 5.9), and *L. taraxacoides* shoot weight and total weight were significantly influenced by irrigation ($P<0.02$) and competition ($P<0.002$) (Table 5.11). Biomass of *A. mearnsii* was unaffected by either irrigation or competition (Table 5.10).

Irrigation

There were a number of between-irrigation treatment differences with respect to target seedling biomass. The mean shoot weight of *E. amygdalina* grown in competition with *A. mearnsii* or *E. amygdalina* was greater with irrigation than without, and the total weight of *E. amygdalina* grown in monoculture was increased by irrigation. The mean shoot weight of *A. mearnsii* grown in monoculture was significantly greater in irrigated than in unirrigated pots. When *L. taraxacoides* seedlings were grown in competition with *E. amygdalina*, shoot weight and total weight were greater with than without irrigation. The shoot and total weight of *L. perenne* grown alone or in monoculture was greater with than without irrigation (Table 5.4, 5.5).

Watering had little effect on mean root weight of *L. taraxacoides*, except where seedlings were grown with *E. amygdalina*, when greater root weight was measured in irrigated than in unirrigated pots (Table 5.6). *L. perenne* root weight was affected by irrigation only when grown in monoculture, when irrigated seedlings had a substantially greater root weight than did unirrigated seedlings.

Intraspecific Competition

Intraspecific competition resulted in significantly greater shoot weight and total weight of *E. amygdalina* grown with added moisture (Tables 5.4, 5.5). When grown with intraspecific competition, the shoot weight of *L. perenne* in unirrigated pots was significantly less than that of seedlings grown alone. Root weight and total weight of this species grown with intraspecific competition was less than that of seedlings grown alone in unirrigated pots (Tables 5.5, 5.6).

Intraspecific competition had no significant effect on the biomass of *L. taraxacoides* seedlings grown with irrigation. When irrigation was not applied, however, both shoot and total weight were significantly reduced by this form of competition (Tables 5.4, 5.5).

Table 5.4. Mean shoot weight (grams) of target species grown with and without competition. Different letters indicate treatment diferences (P<0.05).

Target species	Competing species				
	None	*E. amygdalina*	*A. mearnsii*	*L.taraxacoides*	*L. perenne*
(a) irrigated					
E. amygdalina	0.09^{gh} (0.06-0.12)	0.19^{f} (0.15-0.23)	0.22^{f} (0.17-0.29)	0.07^{gh} (0.05-0.09)	0.07^{gh} (0.04-0.11)
A. mearnsii	0.63^{de} (0.44-0.88)	0.63^{de} (0.54-0.73)	0.81^{d} (0.66-0.98)	-	-
L.taraxacoides	2.17^{bcdef} (0.17-2.63)	4.31^{a} (3.91-4.91)	-	1.23^{cd} (0.81-1.86)	-
L. perenne	2.31^{b} (2.15-2.49)	1.74^{bc} (0.93-3.27)	-	-	1.96^{bc} (1.39-2.77)
(b)unirrigated					
E. amygdalina	0.05^{h} (0.03-0.07)	0.06^{h} (0.05-0.07)	0.11^{g} (0.09-0.13)	0.04^{h} (0.03-0.05)	0.04^{h} (0.03-0.06)
A. mearnsii	0.58^{de} (0.45-0.75)	0.96^{cd} (0.57-1.63)	0.47^{e} (0.42-0.54)	-	-
L.taraxacoides	1.53^{c} (1.38-1.69)	1.66^{c} (1.47-1.85)	-	0.71^{d} (0.58-0.89)	-
L. perenne	1.65^{c} (1.46-1.85)	1.49^{c} (1.32-1.69)	-	-	0.36^{ef} (0.23-0.55)

Interspecific Competition

When compared to seedlings grown in monoculture, competition from *L. perenne* and *L. taraxacoides* significantly decreased shoot weight and total weight of *E. amygdalina* grown with irrigation, and decreased the total weight of seedlings grown with *L. taraxacoides* and no irrigation (Tables 5.4, 5.5). When water was not applied, both shoot weight and total weight of *E. amygdalina* were significantly greater when seedlings were grown in competition with *A. mearnsii* than when grown in monoculture. In irrigated pots, *E. amygdalina* seedlings grown without competition had significantly less shoot weight and total weight than seedlings grown in monoculture.

Without irrigation, both shoot weight and total weight of *A. mearnsii* were significantly increased by competition from *E. amygdalina*. The shoot weight and total weight of *L. taraxacoides* was greater when seedlings were grown with *E. amygdalina* than in monoculture, and root weight was also increased by this form of competition in irrigated pots (Tables 5.4, 5.5, 5.6). Without irrigation, *L. taraxacoides* biomass was also greater with no competition than when grown in monoculture. Without added water, *L. perenne* shoot, total and root weight were all greater in pots with no competition or those with *E. amygdalina* competition than when grown in monoculture. With irrigation, there were no differences in shoot weight or total weight of this species, but root weight was significantly less in pots without competition than when seedlings were grown with competition from *E. amygdalina*.

Table 5.5. Mean total weight (grams) of target species grown with and without competition. Different letters indicate treatment differences (P<0.05).

Target species	Competing species				
	None	*E. amygdalina*	*A. mearnsii*	*L.taraxacoides*	*L. perenne*
(a) irrigated					
E. amygdalina	0.12^{i} (0.08-0.15)	0.26^{g} (0.22-0.31)	0.25^{gh} (0.19-0.33)	0.10^{ij} (0.07-0.14)	0.10^{i} (0.08-0.14)
A. mearnsii	0.49^{f} (0.38-0.64)	0.73^{ef} (0.63-0.85)	0.96^{ef} (0.79-1.17)	-	-
L.taraxacoides	2.61^{cd} (2.17-3.12)	5.21^{a} (4.57-5.77)	-	1.52^{de} (1.05-2.20)	-
L. perenne	3.75^{b} (3.39-4.42)	2.91^{abc} (1.53-5.51)	-	-	3.53^{abc} (2.55-4.89)
(b)unirrigated					
E. amygdalina	0.10^{ij} (0.07-0.13)	0.09^{i} (0.08-0.12)	0.18^{h} (0.16-0.20)	0.06^{j} (0.05-0.07)	0.05^{ij} (0.04-0.08)
A. mearnsii	0.75^{ef} (0.57-0.98)	1.44^{de} (0.83-2.50)	0.69^{f} (0.60-0.79)	-	-
L.taraxacoides	1.74^{d} (1.53-1.98)	2.08^{d} (1.89-2.28)	-	1.05^{e} (0.85-1.29)	-
L. perenne	2.90^{c} (2.57-3.27)	3.21^{bc} (2.75-3.73)	-	-	0.72^{ef} (0.53-0.99)

Table 5.6. Mean root weight (grams) of target species grown with and without competition. Different letters indicate treatment differences (P<0.05).

Target species	Competing species			
	None	*E. amygdalina*	*L.taraxacoides*	*L. perenne*
(a) irrigated				
L.taraxacoides	1.56^{c} (1.44-1.69)	2.99^{b} (2.01-4.46)	1.41^{c} (1.24-1.59)	-
L. perenne	4.96^{b} (3.93-6.27)	11.96^{a} (6.74-21.23)	-	8.62^{ab} (5.17-14.37)
(b)unirrigated				
L.taraxacoides	1.18^{c} (1.18-1.49)	1.51^{c} (1.43-1.60)	1.48^{c} (1.31-1.66)	-
L. perenne	3.86^{b} (3.03-4.13)	6.72^{ab} (3.12-8.82)	-	1.59^{c} (1.39-1.81)

Root nodulation

Although a quantitative analysis of acacia root nodulation was not possible due to damage during the root washing process, at least some nodules were present on every acacia seedling in the experiment.

Competitive Ability

Table 5.7 presents seedling responses to competition as a proportion of the growth of seedlings grown in monoculture. From this, competitive effects can be ranked.

L. taraxacoides competition had a negative effect on the growth of *E. amygdalina*. When combined with its increased growth in response to *E. amygdalina* competition, it would seem that *E. amygdalina* is a poor competitor against this species. *L. perenne* competition also had a negative effect on the growth of *E. amygdalina* seedlings, whereas *E. amygdalina* competition stimulated the growth of *L. perenne*, suggesting that *E. amygdalina* is also a poor competitor against this species.

Competition from *A. mearnsii* increased the shoot weight and total weight of *E. amygdalina* seedlings grown without irrigation, and had no negative effect on other growth parameters. *E. amygdalina* competition did not affect on the growth of *A. mearnsii*. This suggests that *A. mearnsii* and *E. amygdalina* have a low competitive effect on each other.

Table 5.7. Seedling response to competition, given as a proportion of the growth of a seedling grown in monoculture(figures for seedlings grown in monoculture are 1.00). N = no competition, EA = *E. amygdalina*, AM = *A. mearnsii*, LP = *L. perenne*, LT = *L. taraxacoides*.

Target species	Competing species									
	With irrigation					Without irrigation				
	N	EA	AM	LP	LT	N	EA	AM	LP	LT
(a)Height										
EA	0.66*	1.00	1.26	0.64*	0.44*	0.80	1.00	1.13	0.68*	0.61*
AM	0.66*	0.74*	1.00	-	-	1.13	0.85	1.00	-	-
(b) Root length										
EA	0.84	1.00	1.27	1.02	0.93	0.73	1.00	1.01	0.73*	0.77*
AM	0.72*	1.26	1.00	-	-	0.83*	0.88	1.00	-	-
(c)Root to shoot ratio										
EA	2.11	1.00	1.17	1.32	2.08	0.91	1.00	0.89	1.07	1.32*
AM	2.06	1.71*	1.00	-	-	0.73*	1.62*	1.00	-	-
(d) Shoot wt										
EA	0.47*	1.00	1.16	0.36*	0.37*	0.83	1.00	1.83*	0.66	0.66
AM	0.77	0.77	1.00	-	-	1.23	2.04*	1.00	-	-
LT	1.76	3.50*	-	-	1.00	2.15*	2.33*	-	-	1.00
LP	1.17	0.88	-	1.00	-	4.58*	4.13*	-	1.00	-
(e) Total wt										
EA	0.46*	1.00	0.96	0.38*	0.38*	1.11	1.00	2.00*	0.66*	0.55
AM	0.51*	0.76	1.00	-	-	1.08	2.08*	1.00	-	-
LT	1.72	3.43*	-	-	1.00	1.66*	1.98*	-	-	1.00
LP	1.06	0.82	-	1.00	-	4.03*	4.46*	-	1.00	-
(f) Root wt										
LT	1.13	2.12*	-	-	1.00	0.79	1.02	-	-	1.00
LP	0.57*	1.38	-	1.00	-	2.43*	4.22*	-	1.00	-

* indicates significant differences (P<0.05) from growth in monoculture within rows.

Table 5.8. ANOVA table giving the effects of irrigation and level of competition on *E. amygdalina* seedlings.

Treatment	DF	MS	F	p
(a) Height				
Irrigation	1	2.7773	5.25	0.0254
Competition	1	1.4484	2.74	0.0366
Irrigate x competition	4	0.0839	0.16	0.9583
RESIDUAL	61	0.5287		
(b) Root Length				
Irrigation	1	0.1631	0.59	0.4458
Competition	4	0.2562	0.43	0.4555
Irrigate x competition	4	0.0617	0.22	0.9245
RESIDUAL	58	0.2769		
(c) Shoot Weight				
Irrigation	1	8.2667	6.15	0.0159
Competition	4	2.9965	2.23	0.0760
Irrigate x competition	4	0.3001	0.22	0.9243
RESIDUAL	61	1.3531		
(d) Total Weight				
Irrigation	1	4.1438	4.29	0.0426
Competition	4	2.5316	2.62	0.0435
Irrigate x competition	4	0.4133	0.43	0.7881
RESIDUAL	61	0.9666		
(e) Root to Shoot Length Ratio				
Irrigation	1	1.5719	5.67	0.0206
Competition	4	0.5354	1.93	0.1175
Irrigate x competition	4	0.1173	0.42	0.7914
RESIDUAL	58	0.2773		

Table 5.9. ANOVA for the effects of irrigation and competition on the growth of *L. perenne*.

Source of Variation	DF	MS	F	p
(a) Shoot Weight				
Irrigate	1	5.5539	4.34	0.0434
Competition	2	3.4049	2.66	0.0817
Irrigate x competition	2	3.0875	2.42	0.1019
RESIDUAL	41	1.2782		
(b) Root Weight				
Irrigate	1	7.3002	5.59	0.0229
Competition	2	2.9806	2.28	0.1151
Irrigate x competition	2	2.4866	1.90	0.1621
RESIDUAL	41	1.3071		
(c) Total Weight				
Irrigate	1	5.5562	3.48	0.0691
Competition	2	2.8024	2,75	0.0760
Irrigate x competition	2	3.3610	3.29	0.0472
RESIDUAL	41	1.0207		

Table 5.10. ANOVA table for the effects of irrigation and competition on *A. mearnsii* seedling growth.

Source of Variation	DF	MS	F	p
(a) Height				
Irrigate	1	0.3382	2.52	0.1204
Competition	2	0.2323	1.73	0.1903
Irrigate x competition	2	0.2726	2.03	0.1446
RESIDUAL	41	0.1344		
(b) Root Length				
Irrigate	1	0.1969	1.38	0.2472
Competition	2	0.3542	2.48	0.0963
Irrigate x competition	2	0.1932	1.35	0.2700
RESIDUAL	41	0.1429		
(c) Root to Shoot Length Ratio				
Irrigate	1	0.0042	0.01	0.9149
Competition	2	1.0280	2.81	0.0716
Irrigate x competition	2	1.1042	3.02	0.0596
RESIDUAL	41	0.3653		
(d) Shoot Weight				
Irrigate	1	0.0360	0.05	0.8262
Competition	2	0.2569	0.35	0.7079
Irrigate x competition	2	0.9282	1.26	0.2949
RESIDUAL	41	0.7377		
(e) Total Weight				
Irrigate	1	0.6965	0.97	0.3293
Competition	2	0.8341	1.17	0.3213
Irrigate x competition	2	1.1863	1.66	0.2026
RESIDUAL	41	0.7145		

Table 5.11. ANOVA table of the effects of irrigation and competition on the growth of *L. taraxacoides* seedlings.

Source of Variation	DF	MS	F	p
(a) Shoot Weight				
Irrigate	1	3.8744	6.23	0.0168
Competition	2	4.6601	7.50	0.0017
Irrigate x competition	2	0.2883	0.46	0.6322
RESIDUAL	40	0.6215		
(b) Root Weight				
Irrigate	1	0.7392	2.41	0.1286
Competition	2	0.6680	2.20	0.1237
Irrigate x competition	2	0.5272	1.74	0.1887
RESIDUAL	40	0.3032		
(c) Total Weight				
Irrigate	1	3.2720	6.12	0.0177
Competition	2	3.7725	7.06	0.0024
Irrigate x competition	2	0.3174	0.59	0.5570
RESIDUAL	40	0.5345		

Summary of Results

- Competition from *L. taraxacoides* significantly decreased *E. amygdalina* height, both with and without irrigation (Table 5.1), and decreased root length (no irrigation) (Table 5.2), shoot weight (with irrigation), and total weight (with or without irrigation) (Tables 5.4, 5.5).
- Competition from *L. perenne* decreased *E. amygdalina* height (Table 5.1) both with and without irrigation and total weight (with irrigation), and decreased shoot weight (with irrigation) (Table 5.4) and root length (no irrigation) (Table 5.2).
- Intraspecific competition increased *E. amygdalina* height, shoot weight and total weight when irrigation was applied (Tables 5.1, 5.4, 5.5).
- Intraspecific competition increased *A. mearnsii* root length and height (with irrigation), and the root to shoot length ratio (no irrigation) (Tables 5.1, 5.2, 5.3, 5.5).
- *A. mearnsii* competition increased both the shoot weight and total weight of *E. amygdalina* in unirrigated pots (Tables 5.4, 5.5).
- *E. amygdalina* competition decreased the height of *A. mearnsii* seedlings grown with irrigation (Table 5.1), but increased shoot weight and total weight when irrigation was not applied (Tables 5.4, 5.5).
- *L. taraxacoides* shoot, root and total weight were increased by competition from *E. amygdalina* (Tables 5.4, 5.5, 5.6).
- In unirrigated pots, *L. perenne* root, shoot and total weight were greater with *E. amygdalina* competition than in monoculture (Tables 5.4, 5.5, 5.6).
- When *L. taraxacoides* was grown with *E. amygdalina* competition, greater shoot, total and root weight was measured with than without irrigation (Tables 5.4, 5.5, 5.6).
- *E. amygdalina* grown in monoculture also responded to irrigation, with greater height (Table 5.1) and shoot, total and root weight (Tables 5.4, 5.5, 5.6) being recorded in irrigated than in unirrigated pots. The height of *E. amygdalina* grown with *L. perenne* competition increased with irrigation (Table 5.1), but the root to shoot ratio was less with than without irrigation. When *E. amygdalina* was grown with *L. taraxacoides* competition, irrigation had no effect on growth.
- The shoot, root and total weight of *L. perenne* grown in monoculture was greater with than without irrigation.

Discussion

Irrigation

Irrigation had no effect on the root and shoot growth of *E. amygdalina* or *A. mearnsii* seedlings grown without competition. This suggests that moisture was not the main limiting factor when seedlings were grown alone, which is in accordance with the findings of the experiments of the previous chapter. *E. amygdalina* responded to irrigation, however, when grown in monoculture or in competition with *L. perenne*, as did *A. mearnsii* grown in monoculture.

The root to shoot ratio of seedlings was found by Berendse (1981) and Gerakis *et al.* (1975) to increase with moisture stress. Similarly, the root to shoot ratio of *E. amygdalina* grown with *L. perenne*, and *A. mearnsii* grown in monoculture, was greater with increased moisture stress.

Gerakis *et al.* (1975) measured decreased growth of *Bromus* and *Trifolium* roots with moisture stress. In the present experiment, *L. taraxacoides* and *L. perenne* seedlings grown alone did not experience such a decrease in root growth, but, when *L. taraxacoides* was grown with *E. amygdalina*, or when *L. perenne* was grown in monoculture, such a decrease was measured at lower soil moisture. As well, the total weight of *L. taraxacoides* grown alone decreased with moisture stress, as did the shoot weight and total weight of *L. perenne* grown alone. When *L. perenne* was grown in monoculture, shoot and total weight were also increased with irrigation. This strongly suggests that both species were responding to levels of available soil moisture.

Intraspecific Competition

Intraspecific competition stimulated the growth of *E. amygdalina* and *A. mearnsii* seedlings, particularly where irrigation was applied. This is surprising, and contrary to the findings of Webb *et al.* (1983), who measured a significant decrease in the growth of *Eucalyptus delegatensis* grown with another *E. delegatensis* seedling. There are several possible reasons for the result. It may be related to the position of seedlings in each pot. It is possible that seedlings planted close to the edges of the pots had greater access to moisture than seedlings planted in the centre, due to a flow of water between the pot wall and soil, although this may not explain the result in irrigated pots. Soil temperature may have been greater at the sides of the pots than in the centre of the soil mass, resulting in increased growth. Plants grown near the sides of pots may have had greater root growth, and consequent shoot development, due to less compacted soils near the pot edge.

The result may also be related to root microflora. It is possible that when seedlings of *E. amygdalina* and *A. mearnsii* were grown alone in Cambridge field soil, their root microflora, while sustained, was not vigorous and did not contribute greatly to seedling growth. Growing seedlings in monoculture may, because of the increased total root mass in pots, have provided a more favourable growing environment for root microflora in that soil, with resultant stimulation of seedling growth. Soil microflora, and particularly mycorrhizal associations, have been intimately linked with the health and vigour of many Australian native plants (Warcup 1980; Malajczuk *et al.* 1981; Langkamp and Dalling 1982; Jasper *et al.* 1989a; Jasper *et al.* 1989b). If this explanation were correct, it would suggest that propagules of favourable microflora were in low proportions in the Cambridge soil. It is considered by a number of authors that disturbed or agricultural lands can have significantly reduced or altered soil microfloras (Lewis 1980; Jasper 1987; Jasper *et al.* 1989a; Jasper *et al.* 1989b), resulting in poor growth of native species.

That *L. taraxacoides* and *L. perenne* did not exhibit the same increase in growth when seedlings were grown in monoculture may reflect differences in their rooting structure, root microflora or growth tolerances compared to *E. amygdalina* or *A. mearnsii.*

Interspecific competition has been found by other authors to be weaker than intraspecific competition (Fowler 1986; Goldburg 1987). In the present experiment, intraspecific competition was much stronger than interspecific competition for *L. perenne* and *L. taraxacoides* seedlings, resulting in significant decreases in mean seedling weight. With *L. perenne*, this phenomenon was more pronounced in unirrigated than in irrigated pots, suggesting that competition for moisture was at least partially responsible for the result.

Conversely, competition between two eucalypt or acacia seedlings had a weaker effect than did interspecific competition. This may be a result of different rooting patterns between these species and *L. perenne* or *L. taraxacoides*.

Interspecific Competition

Both *L. perenne* and *L. taraxacoides* competition significantly decreased the growth of *E. amygdalina* seedlings, suggesting that these species have a competitive advantage over *E. amygdalina*, both with and without moisture stress. Similarly, Webb *et al.* (1983) found that growth of *E. delegatensis* was decreased by competition from the grass *Poa labillardieri*. In unirrigated pots, the root weight of *L. perenne* was stimulated by competition from *E. amygdalina*, which is analogous to the findings of Webb *et al.* (1983), who measured an increase in the root weight of *Poa* grown in competition with *E. delegatensis*. The shoot weight and total weight of *L. taraxacoides* were also stimulated by competition from *E. amygdalina*. The reasons for such a growth response are unclear, but may be related to increased nutrient concentrations in the vicinity of eucalypt roots, due to the presence of root microflora. Further research is required before the phenomenon can be adequately explained.

While, in unirrigated pots, the total weight and shoot weight of *L. perenne* was greater with competition from *E. amygdalina* than in monoculture, these parameters also increased when seedlings were grown alone, suggesting that competition from *E. amygdalina*, while increasing root weight, had no real effect on the total or shoot weight of *L. perenne* seedlings. Likewise, the shoot and total weight of *L. taraxacoides* grown in unirrigated pots increased when seedlings were grown alone or with *E. amygdalina*. The results probably reflect the poor competitive ability of *E. amygdalina* seedlings.

Although the height of *A. mearnsii* was unaffected by competition from *E. amygdalina* in pots with no irrigation, both shoot weight and total weight were increased. As well, shoot weight and total weight of *E. amygdalina* increased with competition from *A. mearnsii*. It could be that at low soil moisture levels the species had complementary tolerances. Alternatively, growing these seedlings together may have increased the probability of inoculation by favourable root microflora, although Malajczuk *et al.* (1981) found that colonization levels of vesicular-arbuscular mycorrhizae in eucalypts were not increased when seedlings were grown with acacias. Malajczuk *et al.* (1981), however, do not discount the possibility of the sharing of common vesicular-arbuscular fungal symbionts between eucalypts and acacias, and suggest that such an association may be advantageous to both legumes and eucalypts.

Rhizobial nodules were found on the roots of all acacia seedlings in the experiment. Such nodules are the result of a symbiosis between nitrogen fixing *Rhizobium* bacteria and acacia seedlings, an association which is common to many legumes (Stevenson 1982), and which is believed to be important in the establishment of legumes on nitrogen-poor sites. Adams and Attiwill (1984a, b) reported rates of nitrogen fixing of 12 - 32 kg ha^{-1} $year^{-1}$ for acacias growing as an understorey in temperate eucalypt forest. Langkamp *et al.* (1979) measured a rate of nitrogen fixation of 8 - 16 kg ha^{-1} $year^{-1}$ under acacias at a site in northern Australia. Greater concentrations of both total and mineralizable nitrogen have been found at sites in which acacias are growing (Langkamp *et al.* 1979; Langkamp *et al.* 1982; Ellis and Graley 1987; Ellis and Pennington 1989), although much of this increase has been attributed to the decomposition of plant parts (Adams and Attiwill 1984; Ellis and Pennington 1989). Langkamp *et al.* (1982), however, found that small quantities of nitrogen were leached into the surrounding soil from acacia roots and shoots. Such a phenomenon may account for the increased growth of *E. amygdalina* seedlings grown in competition with *A. mearnsii*. This may have been more pronounced if similar vesicular-arbuscular mycorrhizae were present on the roots of both species, perhaps enabling transfer of nutrients between species (Malajczuk *et al.* 1981).

In studies of the effects of competition on the growth of *Q. douglasii*, Gordon *et al.* (1989) found that the fibrous roots of the annual grass *Bromus diandrus* had a greater competitive effect than did the forb *Erodium botrys*, which they related to a greater ability to compete for moisture. Stronger competitive effects of grasses compared to broadleafs have also been demonstrated by other authors (Gerakis *et al.* 1975; Berendse 1981; Goldburg and Fleetwood 1987). However, Gordon *et al.* (1989) also measured suppression of *Q. douglasii* seedlings grown in competition with *Erodium*, which they hypothesized was related to competition for nutrients. In the above experiment, both *L. taraxacoides* and *L. perenne* had a similar competitive effect, both with and without irrigation. Because stomatal conductance, nutrient status and soil water potential were not measured, it is difficult to discuss reasons for the result.

Conclusions

In the previous chapter, direct-sown eucalypts were shown to exhibit pronounced growth inhibition. In this experiment, however, growth check was much less severe. This may be related to the use of transplanted rather than direct sown seedlings in this experiment. Ellis and Pennington (1985) similarly found that *E. delegatensis* seedlings transplanted at the two leaf stage were less inhibited than those sown directly into pots.

In the field experiment described in Chapter 3, it was demonstrated that growth suppression of the seedlings of three eucalypt species could be overcome with weed control, whether irrigation was applied or not. In subsequent glasshouse work, it was speculated that the growth check of *E. amygdalina* was related to a nutrient imbalance, which was exacerbated by competition from weeds. The experiment described above has demonstrated that both a fibrous-rooted grass species and a tap-rooted broadleaf could have significant negative effects on the growth of *E. amygdalina*, which were not alleviated by the removal of water stress. While responses to weed competition are likely to vary between species, this result illustrates the importance of weed control in the establishment of eucalypts on pasture sites. The effect of weed competition has been found to be related to the density of competing species and the size of the soil mass available for growth (Harper 1977; Goldburg and Fleetwood 1987; Gurevitch *et al.* 1990). Ross and Harper (1972) consider that an advantage gained by an individual over its neighbours is likely to be maintained or accentuated during subsequent growth, but when species have differing rooting patterns (ie deep versus shallow rooted) this must be related to the severity of root growth inhibition. Indeed, Sands and Nambiar (1984) found that inhibition of *Pinus radiata* by weeds decreased as the age of *P. radiata* seedlings increased, with a consequent increase in growth of pine seedlings. This they attributed largely to the relative difference between trees and weeds in root distribution with depth, which changed with age. Eucalypts are more deep-rooting than *L. perenne* or

L. taraxacoides, which may permit coexistence between these species once eucalypt roots have grown through the rooting zone of the weed species. There are numerous examples in grasslands throughout Australia supporting this.

Both *L. taraxacoides* and *L. perenne* have the ability to establish rapidly and compete vigorously with other plants, whether of a different or the same species. They may therefore be able to affect the germination, survival and growth of eucalypt seedlings, through competition. Their ability to emerge more rapidly on bare soil than eucalypts, gives them a competitive advantage, as they can claim a greater proportion of growth resources (Ross and Harper 1972; Firbank and Watkinson 1987). This equates with the inhibition model of succession discussed by Connell and Slatyer (1977), which suggests that the first occupants of a site pre-empt the space and will continue to exclude or inhibit later colonists until the former die or are damaged and resources are released. It is only at this stage that later colonists can establish. This highlights the importance of continuous weed control in the establishment of eucalypts in pasture, from which there is generally a continuous and prolific supply of weed seeds.

The experimental results suggest that *A. mearnsii* and *E. amygdalina* may be able to coexist with few adverse effects on growth, and may stimulate the others' growth, although further testing is required in a field situation. It is possible that, in the field, establishing acacias with eucalypts, particularly on harsh sites, may increase early growth of eucalypt seedlings, thereby promoting establishment. This, however, requires more detailed study with a wider range of species and soil types.

CHAPTER 6. General Discussion

What causes establishment problems?

Salisbury and Ross (1978) describe normal plant growth as having two distinct phases. The first ('exponential' phase) is the rapid increase in plant size representative of early growth. Following this, there is a phase in which size continues to increase, but more slowly ('senescent' phase). Together, these phases result in the sigmoidal growth curve commonly associated with normal plant growth.

Eucalyptus amygdalina seedlings grown in potting mix displayed normal exponential growth during early development. When grown in pasture or remnant woodland soil, however, early growth was not exponential, but markedly suppressed. There are numerous other examples where growth does not conform to the pattern of Salisbury and Ross (1978). The inhibition of *Eucalyptus delegatensis* seedling growth at high altitudes is one well-researched Australian example. *E. delegatensis* seedlings suffering growth inhibition, or 'check', have a greatly reduced growth rate; rounded, bushy crown shape with little apical dominance; smaller, thicker leaves; and few leading shoots (Keenan and Candy 1983). Orme (1971) related growth check in this species to grass competition, which was confirmed in subsequent experiments by Webb *et al.* (1983) and Ellis *et al.* (1985). Orme (1971) found that sterilizing the soil with methyl bromide resulted in a short-term recovery from growth check. Ellis *et al.* (1985) concluded that growth check of *E. delegatensis* at some sites was related to low rates of soil nitrification under grassland, and consequent low nitrogen availability, which was exacerbated by competition between eucalypt seedlings and grass. Similarly, inhibition of *Eucalyptus pilularis* seedlings grown in *E. pilularis* forest soil was found by Florence and Crocker (1962) to be related to low rates of soil nitrification, and the presence of antagonistic soil microflora. Nunez and Bowman (1986) linked growth check of *E. delegatensis* at some sites to a high incidence of frost in clearfelled coupes. Battaglia and Wilson (1991) suggested that growth check is due to an interaction of factors, including frost, browsing, grass competition, nutritional imbalances, and insect attack.

The growth inhibition of *E. amygdalina* seedlings demonstrated in this work appeared to be, at least partially, related to a nutrient imbalance, a phenomenon which was shown to be exacerbated by competition from weeds. Soil sterilization experiments suggest that growth check may also be related to soil microflora. Whether these factors contribute to poor growth of other eucalypt species at other sites in the Midlands in unknown. The specific nutrients associated with any imbalance have not been identified, although it is hypothesized that nitrogen, phosphorus and/or copper may be important. Similarly, the involvement of soil microflora have not been researched. The phenomenon of growth check is apparently not only associated with developed pasture soils, but may contribute to poor eucalypt recruitment on some residual native bushland blocks.

Seedling regeneration following logging in dry sclerophyll forest is commonly associated with fire, with resultant healthy, vigorous seedlings where the soil has been sufficiently heated (Mount 1979; Duncan 1988). In natural ecosystems, Mount (1979) considers that fire plays an integral part in eucalypt regeneration in dry sclerophyll forest and woodland. He observed that such forests are generally multi-aged, with each age corresponding to a previous fire. However, seedling recruitment does not necessarily occur after every fire, but is associated with very intense fires or localized ashbed effects related to the burning of fallen limbs and trunks. Orme (1971) reported good growth of *E. delegatensis* direct sown onto burnt soils, while seedlings on unburnt sites exhibited growth check. Geard (1987) recorded greater growth of eucalypts on pasture sites in the Midlands where a hot burn was achieved prior to direct seeding. In a detailed study of the ashbed effect, Renbuss (1968) found that high intensity burns, and the resultant soil sterilization, significantly altered the soil microbial population and nutrient status, a phenomenon which also occurred if soil was heat sterilized at temperatures of 70°C or greater. Warcup (1981) measured similar soil microbial changes in heat sterilized soil. Early microbial colonizers of the sterilized soil have been found to differ dramatically from the populations in soil prior to sterilization, a difference which often persists for a considerable time after soil treatment (Renbuss 1968; Ahlgren 1974; Warcup 1981; Attiwill and Leeper 1987). Levels of nitrogen and phosphorus have also been found to increase in heat sterilized soil (Renbuss 1968; Humphreys and Craig 1981), although Renbuss (1968) found that concentrations of both nutrients decreased rapidly with time after treatment. She measured significant increases in the growth of eucalypt seedlings in ashbed soil, and Warcup (1981) discusses a similar response in *E. regnans* seedlings grown in heat sterilized soil. Such growth stimulation has been found to coincide with the time taken for the heat-induced soil microflora to revert to its pre-heating state (Renbuss 1986). The roots of seedlings grown in sterilized soil were found to have significantly less root tips infected by micro-organisms than the roots of seedlings grown in untreated soil, and faster growth rates were measured in seedlings with less infected root tips (Renbuss 1968). Warcup (1981) found that the roots of seedlings grown in heat sterilized soil had fewer types of mycorrhizal fungi present than did the roots of seedlings grown in untreated soil.

A similar growth stimulation was measured when *E. amygdalina* seedlings were grown in sterilized soil, and although soil factors were not investigated, it is possible that adverse microbial populations were partially responsible for the growth check measured in *E. amygdalina* seedlings. That inhibition was overcome by additions of nutrients as well as by heat sterilization suggests either that sterilizing the soil increased the concentration of available nutrients, thereby increasing growth, or that soil microflora effectively competed for nutrients, and the addition of nutrients in the form of fertilizer overcame this problem. It can be concluded that soil factors had a major inhibitory effect on *E. amygdalina* seedling growth, and may be a significant factor contributing to poor establishment of other eucalypts on pasture and woodland sites in the Midlands. Further research in this area is required.

As well as growth inhibition, germination and survival problems were recorded , which were found to be associated with a number of factors. Increasing soil moisture via irrigation was found in pot trials to increase *E. amygdalina* germination and survival, which agrees with the findings of many other authors (eg Edgar 1977; Cromer 1980; Attiwill and Cromer 1982; Bachelard 1985; Gibson and Bachelard 1986). This result suggests that periodic drought, of both long and short duration, is likely to contribute to poor germination and survival of eucalypt seedlings in the Midlands, although moisture availability may not be a critical factor influencing seedling growth. Cunningham (1960) and Cremer (1962) found that drought was a serious cause of death in *Eucalyptus regnans,* although most mortality due to drought was recorded in cotyledonous and two leaf pair seedlings. Cremer (1962) considered that most drought-related deaths were likely to occur during spring and summer in the Florentine Valley, due to high precipitation and low evaporation in the other seasons. In the Midlands, however, winter drought conditions may occur at some sites in some years (Anonymous 1975).

The climate in the Midlands is harsh, and clearing for pasture development has probably increased exposure to insolation, wind and frost. Similarly, greater temperature extremes, increased incidence of frost, and greater occurrence of drought have been recorded in clearfelled logging coupes than in partially or unlogged forests, with consequent regeneration problems (Nunez and Bowman 1986; Childs and Flint 1987; Flint and Childs 1987). Very high and low temperatures were recorded close to the soil surface at experimental sites in the Midlands, both of which can cause tissue damage in plants. Such damage is generally only fatal to cotyledonous seedlings (Cunningham 1960; Cremer 1962; Nobel 1984), although Grose (1957) recorded frost mortality in larger eucalypt seedlings, and in Tasmania mature trees have been known to be killed by severe frosts (eg Calder 1850). Cremer (1962) considered tissue damage due to frost to be less severe than frost heave in the Florentine Valley in Tasmania. Frost heave was not observed at any Midlands site, although it may be a problem in some areas. Cunningham (1960) intimates that frost damage may be more severe during unseasonally cold conditions, when seedlings have not undergone a period of frost hardening. Frosts in spring, summer and autumn may therefore have a greater impact than those in winter. In the Midlands, frosts are recorded in all seasons, often followed by high temperatures.

Cunningham (1960) measured soil surface temperatures in excess of 60°C in logging coupes in Victoria, although it was unclear from his studies what the critical temperature for mortality was. Nobel (1984) found that desert succulents could tolerate temperatures in excess of 60°C when acclimatized to high temperatures, but that tolerance to such temperatures decreased with temperature variability. Cunningham (1960) concluded that high soil surface temperatures may be an important cause of death in *E. regnans* seedlings germinating in spring and summer in logged coupes. High temperatures close to the soil surface were recorded at experimental sites in the Midlands, and it is likely that such temperatures contributed to seedling mortality. In field situations high temperature mortality and dehydration are almost impossible to separate, and hence it is possible that greater high temperature mortality occurs than is generally recorded.

Both Geard (1987) and Parker (N. Parker, Forestry Commission, Tasmania, pers. comm.) have successfully regenerated, without burning, recently-cleared *E. amygdalina* forest sites in the Midlands by direct seeding, and seed regeneration of such sites following logging is a routine operation by forestry companies operating in the area. In Chapter 4, however, it was demonstrated that *E. amygdalina* growth was inhibited in soil collected from a remnant bushland block. Mature eucalypts in this block were declining, whereas the eucalypts cleared from the sites of Geard and Parker's trials formed a healthy mature forest. This suggests that environmental factors in the declining remnant bush block did not favour eucalypt regeneration, although a stimulant such as fire may have enhanced results. In the newly-cleared forest sites, soil factors probably more closely approximated those found in a healthy forest stand, which may have accounted in part for the good establishment on such sites. Both sites were in close proximity to healthy forests, which may have provided protection from some environmental conditions. That acceptable results were achieved on these sites suggests that direct seeding may be a useful technique on less degraded areas in the Midlands, such as newly-cleared areas or native pasture sites.

How can establishment problems be overcome?

In many parts of Australia, direct seeding is used effectively for tree establishment on pastoral sites. Failures are generally poorly publicized. In Tasmania, failure of direct seeding in commercial forestry has been associated with high altitude and grassy sites (Battaglia 1990a; 1990b), and on pastoral lands in the Midlands there have been consistently poor results. The preceding experiments have demonstrated that at least on some sites in the Midlands, poor establishment and growth of eucalypts is related in part to ecological factors. As well as possible soil biological factors, clearing and pasture development have probably increased exposure to insolation, wind and temperature extremes, and exotic pasture species compete strongly for resources with any emergent native tree or shrub seedlings. There are a number of ways in which results may be enhanced.

Soil preparation which increases the number of niches providing protection from drought and extreme temperatures may increase the number of seedlings emerging and surviving at a particular site. Flint and Childs (1987) found that harsh environmental conditions necessitated site modification for the successful regeneration of Douglas fir. Cardboard shadecards, mulching with black plastic, and removal of competing vegetation all increased the establishment of planted seedlings. All treatments resulted in greater soil moisture availability, and mulching and shading decreased soil temperatures. Childs and Flint (1987) found that partial logging, as opposed to clearfelling, modified environmental conditions by decreasing solar radiation at the soil surface, with resultant cooler soil temperatures, which improved seedling growth. Similarly, Nunez and Bowman (1986) recorded substantially reduced frost incidence in unlogged or partially logged *E. delegatensis* forest than in clearfelled areas. In the Midlands, Geard (1987) found that shelter from inverted plastic cups increased emergence and short-term survival of native seedlings. Lockett (1978) recorded similar results on difficult to regenerate commercially logged sites. On mainland Australia, site modification has led to successful tree establishment on pasture sites in low rainfall areas (Malcolm and Allen 1981; Dalton 1990; Odermatt 1990). Niche seeding techniques, such as soil pitting and furrowing, have been used successfully (Malcolm and Allen 1981; Loney 1990; Odermatt 1990; Walker 1990), and Hinz (1990) and Duckett (1990) reported acceptable results from spreading slash material over direct sown sites. Dalton (1990) found that mulching with black bituminous spray gave good results, and Duckett (1987) and Burns (1987) suggested using a cover crop to protect emergent seedlings.

In the experiments reported in previous chapters, neither deep ripping, soil scalping nor mulching greatly affected seedling emergence or survival, although some treatments performed better than others. Similarly, sowing a cover crop had no effect on results. It is possible that these treatments did not significantly increase the number of safe germination niches. Sheldon (1974) considers that as conditions become more harsh, the number of safe sites diminishes, and thus a greater microsite variation is required to provide suitable establishment sites. The machine used for sowing may have contributed to poor results in ripped and scalped soil. The Western Tree Seeder sows seed into a furrow approximately 10 cm wide and 1 cm deep, and the sowing process probably reduces the number of safe germination niches. Greater emergence and survival were recorded at the Cambridge field site, where rough cultivation was followed by hand sowing, than on sites sown with the Western Tree Seeder, which may have been related to differences in microsite variation, or simply to site and year. If riplines had not been smoothed prior to sowing, better results may have been achieved from this treatment. Open riplines may provide seedlings with shading and protection from extreme temperatures.

The previous experiments strongly suggest that an important component of site preparation is weed control. This was found with *E. amygdalina* to be partlyrelated to competition for nutrients, although competition for moisture and other resources may have been a factor. Both broadleaf and grass species were implicated in this. Similarly, other authors have also recorded increased growth and survival from weed control (Revell 1976; Nambiar and Zed 1984; Nazer and Clark 1984; Ellis *et al.* 1985; Gordon *et al.* 1989). The importance of long term weed control was clearly demonstrated in both field and glasshouse experiments, as was the difficulty in achieving this. The most effective methods of accomplishing long term weed control were pre-emergent applications of residual herbicide, and soil scalping. It was unclear whether the use of pre-emergent herbicide affected germination of sown seed, but this has certainly been demonstrated in other Australian states, and most authors warn that native seed should not be sown directly into soil sprayed with residual herbicide (Dalton 1990; Bird *et al.* 1990). Soil scalping, while effective in controlling weeds, did not appear to increase seedling emergence or survival after 7 months. It is a technique which is not suitable for all sites, particularly those which are sandy or steep, and therefore has limited application. Emergence and survival on scalped soil may, however, be increased by either rough cultivation or deep ripping following scalping, to increase microsite heterogeneity.

Knockdown herbicide was found to give relatively short periods of weed control, which suggests that if such herbicides are used for pre-sowing weed control, follow-up applications will be required. While Bird *et al.* (1990) had some successes from overspraying seedlings with knockdown herbicides, this is generally not recommended. Overspraying with selective herbicides may leave seedlings competing with broadleaf weeds, which were shown in the above experiments to significantly affect eucalypt seedling growth. In some instances, overspraying with residual herbicides may provide good weed control without adversely affecting seedlings (Wilkinson and Neilsen 1990; Bird *et al.* 1990), although results may be dependent on species and seedling size.

Whilst most authors working on tree re-establishment on pasture sites in southern Australia consider spring to be the most favourable time for sowing (Geard 1987; Venning 1988), it may be that when conditions are harsh, earlier sowings are more appropriate. It was demonstrated in the previous experiments that a greater soil moisture content increased germination and survival. Sowing at a time of year when soil moisture is greater and there are less intense wetting and drying cycles may result in greater seedling recruitment in the field. Less extreme soil temperatures may also enhance results. Cunningham (1960) found that seedling mortality in autumn-sown germinants was high during the following winter, and was also great for spring-sown seed during the following summer and winter. He suggested that providing shelter to sites would reduce mortality during winter and the following summer. In Tasmania, most prescriptive sowing in forest operations occurs in autumn (Lockett 1991), which it is considered provides the most suitable germination conditions if adequate site preparation has been undertaken. Spring sowings have generally been recommended for pasture sites principally because weed control is more easily achievable, and because the possibility of frost occurrence is reduced. Cunningham (1960), however, measured most frost damage in spring rather than winter, which may be related to the hardening-off process which occurs in winter. If adequate autumn weed control can be achieved, and soils are modified to provide sheltered germination niches, it may be that autumn or winter sowings would give better results than spring sowings on many sites in the Midlands. In the time of sowing experiments outlined in Chapter 2, sowing in July rather than September resulted in greater germination, although seedling survival did not increase.

In a situation of low soil water content, it was shown that association with *A. mearnsii* stimulated the biomass production of *E. amygdalina*. It is possible that acacias can influence the nutrient balance, either via leaching of nitrogen from acacia root and shoot material (Langkamp *et al.* 1982), from an interaction between eucalypt and acacia fungal symbionts (Malajzcuk *et al.* 1981), by increasing rates of soil nitrification (Ellis and Pennington 1989), or in the long term by enhancing soil nitrogen due to the decay of plant material (Langkamp *et al.* 1979; Ellis and Graley 1987; Ellis and Penningon 1989). It may be that including a large proportion of acacias in the sowing mix will ultimately increase eucalypt growth in the field. In glasshouse experiments, *A. mearnsii* and *E. amygdalina* appeared, both with and without irrigation, to have a low competitive effect on the other species, which suggests that acacias could be used in the field as a cover crop for emergent eucalypts, providing shade and shelter as well as enhancing nitrogen nutrition.

Direct seeding will possibly be more successful on some sites than others. In broadacre trials it was observed that results were worse on sandy soils, which was probably related to the poor water-holding capacity of such soils. Sites which offer protection from wind, temperature extremes and severe weed competition may be more successful than exposed sites such as exposed north-facing slopes. Newly-cleared or native pasture sites may give better results than sites which have been degraded through long term pasture establishment.

Soil nutritional imbalances may be overcome in the field by additions of appropriate nutrients. Ellis *et al.* (1985) found that growth check in *E. delegatensis* could be overcome by additions of nitrogen and phosphorus, and Florence and Crocker (1962) had similar results with *E. pilularis* seedlings suffering growth inhibition. Ward *et al.* (1985) measured a significant growth response in *E. saligna* (Smith.) seedlings exhibiting symptoms of nutrient deficiency, to applications of nitrogen and phosphorus. In a detailed review of the effects of fertilizer application on eucalypt growth, Schonau and Herbert (1989) outlined that there was generally a positive response to the addition of fertilizer, but that the degree of response depended on the site and species. In the field experiment in Chapter 3, fertilizer addition when combined with initial weed control had no consistent effect on eucalypt seedling height growth. In subsequent glasshouse experiments however, there was found to be a substantial growth response from *E. amygdalina* to fertilizer addition in the presence of weed control. It was also demonstrated that fertilizer, in combination with irrigation, increased weed weight, and in the absence of irrigation significantly decreased germination of *E. amygdalina*. It was concluded that fertilizer addition at the time of sowing is probably inappropriate. Although the decreased germination demonstrated in the glasshouse was not measured in the field, germination may be affected at other sites, and even if it is not, it seems unnecessary to apply fertilizer at a time when it cannot be utilized by eucalypt seedlings, and may in fact stimulate the growth of weed seedlings. A more appropriate time of application may be post-emergence. The glasshouse and field experiments illustrated the importance of weed control if fertilizer is to be applied.

Both soil sterilization and nutrient addition overcame growth check in *E. amygdalina*. This suggests that fire may be a useful tool in localized areas in the Midlands, with its capacity to sterilize the soil and increase nutrient availability. Geard (1987) reported good establishment and growth of eucalypts on burnt sites in the Midlands. He achieved hot burns by heaping and burning dead trees in locations where vegetation was desired. On many sites, however, this method would be impractical.

Ecological implications

In terms of the establishment of trees on farms in the Midlands, there are three possible courses of action. The first is to continue in the present manner, attempting to re-establish trees and shrubs by direct seeding, nursery propagation and natural regeneration, but with high mortality where direct seeding is concerned, poor growth on many sites regardless of technique, and little understanding of the causes of regeneration problems. Alternatively, exotic species better able to grow in the Midlands could be substituted for native species. However, if this course is taken, the ability to rejuvenate the natural ecology may be lost forever. Both of these approaches, with their emphasis on tree establishment rather than other forms of vegetation, are probably symptomatic of a 'quick fix' attitude, in which there is little or no attempt to understand the ecology of the system and hence the origins of the problem.

A more appropriate approach may be to work from the 'bottom up' rather than the 'trees down' as is generally attempted, with emphasis on soil biology and the role of native grasses, herbs and shrubs in site modification. Studies of old-field revegetation have illustrated that there is often only a slow colonization of such sites by trees (Ellis 1974). Read (1982) suggests a general pattern of vegetation development in old-fields, which begins with annual and perennial herbs, and climaxes with woody vegetation. She contends that a species must be able to tolerate the physical conditions of its environment before it can establish, and must be able to compete effectively with other plants for limited resources. The experimental work outlined in the previous chapters has clearly demonstrated that eucalypt seedlings cannot tolerate environmental conditions in exotic pasture sites in the Midlands, and this restricts their establishment potential. If eucalypts are to be successfully re-established on a broad scale on such sites in the Midlands, an understanding of the processes inhibiting their establishment is critical, as is knowledge of natural vegetation establishment and successional processes in that environment.

A number of fundamental areas for research have been identified during the course of this project. While a number of the ecological impediments to the establishment of three eucalypt species by direct seeding at one site in the Midlands have been identified, further research is required at a range of locations with a range of species, both within and outside the Midlands, to develop a greater understanding of the problems associated with revegetation, and to identify methods of overcoming these. A study of possible reasons for the successful establishment of vegetation by direct seeding in apparently similar environments on the mainland would seem appropriate. Of critical importance is a study of soil biology, with emphasis on rates of nitrogen mineralization, soil nutritional status, and microflora. Linked to this should be a study of the natural regeneration and successional processes operational in more natural ecosystems in the Midlands, and investigation of the soil biology of healthy forest stands within and outside the area.

Also of importance are a study of methods for achieving long-term weed control without reducing seedling emergence, survival and growth; the field significance of safe germination sites; the importance of site variation; the role of fire in site preparation on agricultural and bushland sites; and methods of manipulating the time of sowing through site preparation. As well, it is important to monitor the fate of seedlings in the long term. There have been reports in the Midlands of trees planted 10 years earlier suffering from rural dieback (N. Parker pers. comm.), and it is essential to determine whether a similar fate is met by all direct-sown or hand-planted seedlings. Re-establishing pockets of vegetation in which natural processes can more effectively occur may be one means of overcoming the problem of longevity, but this requires study. Further investigation of the interactions of eucalypts and acacias may be useful, as could be a study of the extent and effect of seed harvesting activities.

Conclusions

Whilst it is probably premature to totally discount direct seeding as a technique for revegetation in the Midlands of Tasmania, there are obviously problems associated with it in some locations in this region. Results may be improved by appropriate site selection, preparation to allow long term weed control and microsite variation, and appropriate species selection and time of sowing. A better understanding of soil biological factors, and a change in emphasis from 'tree' to 'vegetation' re-establishment, will probably contribute considerably to the development of effective direct seeding prescriptions.

The conclusion of the experiments presented in this work contradict many of the views from around Australia regarding direct seeding. There is insufficient information available at present to explain this. The problems encountered may not be related only to direct seeding, as the Midlands suffers from severe rural tree decline (McMurray 1988), and slow growth and crown dieback have been reported for hand planted seedlings (N. Parker, Forestry Commission, Tasmania, pers. comm.).

In terms of farm tree re-establishment, hand planting must still be considered a more effective method of vegetation establishment in the Midlands than direct seeding. Despite growth problems in some instances, survival of at least 75% of planted seedlings can be achieved if appropriate techniques are used. Such seedlings are more resilient to temperature xtremes and drought than direct-sown seedlings, because of their size at the time of planting. However, these techniques are expensive and not suited to broadacre revegetation of the scale needed to redress land degradation problems in the Midlands. With further research, direct seeding may eventually provide a cheap and effective means of such broadscale farm revegetation.

APPENDIX 1. Site Descriptions

General Description

The Midlands of Tasmania lies between the Eastern and Western Tiers, extending from Launceston to Hobart, into the Fingal and Coal River valleys, and up the Derwent Valley as far as Hamilton (Figure A1.1). It is an area of varied relief underlain mainly by sediments of the Parmeener Supergroup that are intruded by dolerite and basalt. Minor areas of Precambrian, Cambrian and Ordovician basement rock that have experienced at least one orogenic event are also found (Davies 1988).

The area experiences one of the more extreme climates in the state. Rainfall averages between 450 - 700 mm per annum, with occasional fluctuations below 300 mm or above 1100 mm. Rainfall is spread evenly through the seasons, but due to extreme differences in evapotranspiration in each season, available soil moisture fluctuates dramatically. Annual rainfall fluctuates considerably between seasons, with a coefficient of variation of 14% in the north of the region and 17% in the south (Anonymous 1972).

Summers are warm, with average air temperatures ranging between 7.9°C and 22.1°C (Anonymous 1972), although temperatures of -9° C and 50°C have been recorded close to the ground. In winter, average temperatures range from 1.3°C to 10.7°C.

Strong winds are often experienced in the area from September to November, predominantly from the west and south-west. Hot dry winds are experienced from the north during summer. Light frosts can occur between January and November, with heavy frosts between March and October (Anonymous 1972). Snow falls occasionally.

Table A1.1. Summary of Climatic conditions experienced in the Midlands.

Location	Season	Av.rainfall	%annual rainfall	Av Temp (Max)°C	Av. Temp (Min)°C	Evapotranspiration (mm)
Oatlands	Spring	15.0	26	15.1	4.2	9.9
	Summer	14.4	25	20.7	7.8	14
	Autumn	13.5	24	18.4	4.9	8.5
	Winter	13.9	25	9.8	1.5	5.2
Campbell Town	Spring	16.6	28	16.2	4.5	10.4
	Summer	14.3	24	22.4	8.4	18.5
	Autumn	13.2	22	16.9	5.0	8.3
	Winter	15.3	26	10.9	0.8	3.6

Land in the Midlands is used primarily for grazing and cropping. Localized cropping of cereals, vegetables such as potatoes, and forage material occurs on the deeper soils in lowland areas (Davies 1988).

Grazing is the most widespread landuse in the area (Davies 1988), and ranges from grazing of improved pasture on flats and gentle slopes to rough grazing of native pastures on steep country. In the driest areas, grazing is widespread. Sheep and beef cattle are the major livestock. Deer farming occurs in some areas.

Forestry operations are conducted around the perimeter of the Midlands, mainly on private land and principally for woodchips. In localized areas, mining for lateritic gravels and sand have occurred.

Vegetation in the dry areas of the Midlands is principally grassy forest and woodland. Much has been cleared for agriculture and some for woodchips. Around the periphery of the region, wet forest is found, in which forestry is a significant landuse (Davies 1988).

Land degradation problems such as soil erosion, soil salinity and tree decline are prevalent in many areas of the Midlands (Temple-Smith 1988). Much of the existing erosion damage was initiated by and the result of intensive cropping in many districts during the first century of white settlement (Davies 1988). There has been a gradual stabilization in many areas, but severe problems still exist. Tunnel erosion is a major problem in mudstone and sandstone country. Sheet, rill and gully erosion are found throughout the area on a wide range of land types. Landslips occur on mudstone and sandstone sequences of the Parmeener Supergroup, but also to a lesser extent on steep slopes on other rock types. Flooding and waterlogging occur on flat lowlying areas. Salting problems are found along some drainage lines and in some lowlying areas.

Decline of remnant vegetation is a major problem in the Midlands, and is particularly obvious in the north of the region. Trees are affected by a combination of old age, drought, insect and possum browsing, the adverse effects of increased soil fertility, and landuse practices such as regular ploughing (McMurray 1985b; 1988). Grazing of remnant areas and the introduction of improved pasture species and chemical fertilizers has, in many instances, precluded regeneration under remnant trees.

Study Site Descriptions

Generalized descriptions of the sites used for experimental work are given in Table A1.2. The location of each site in the Midlands is presented in Figure A1.1.

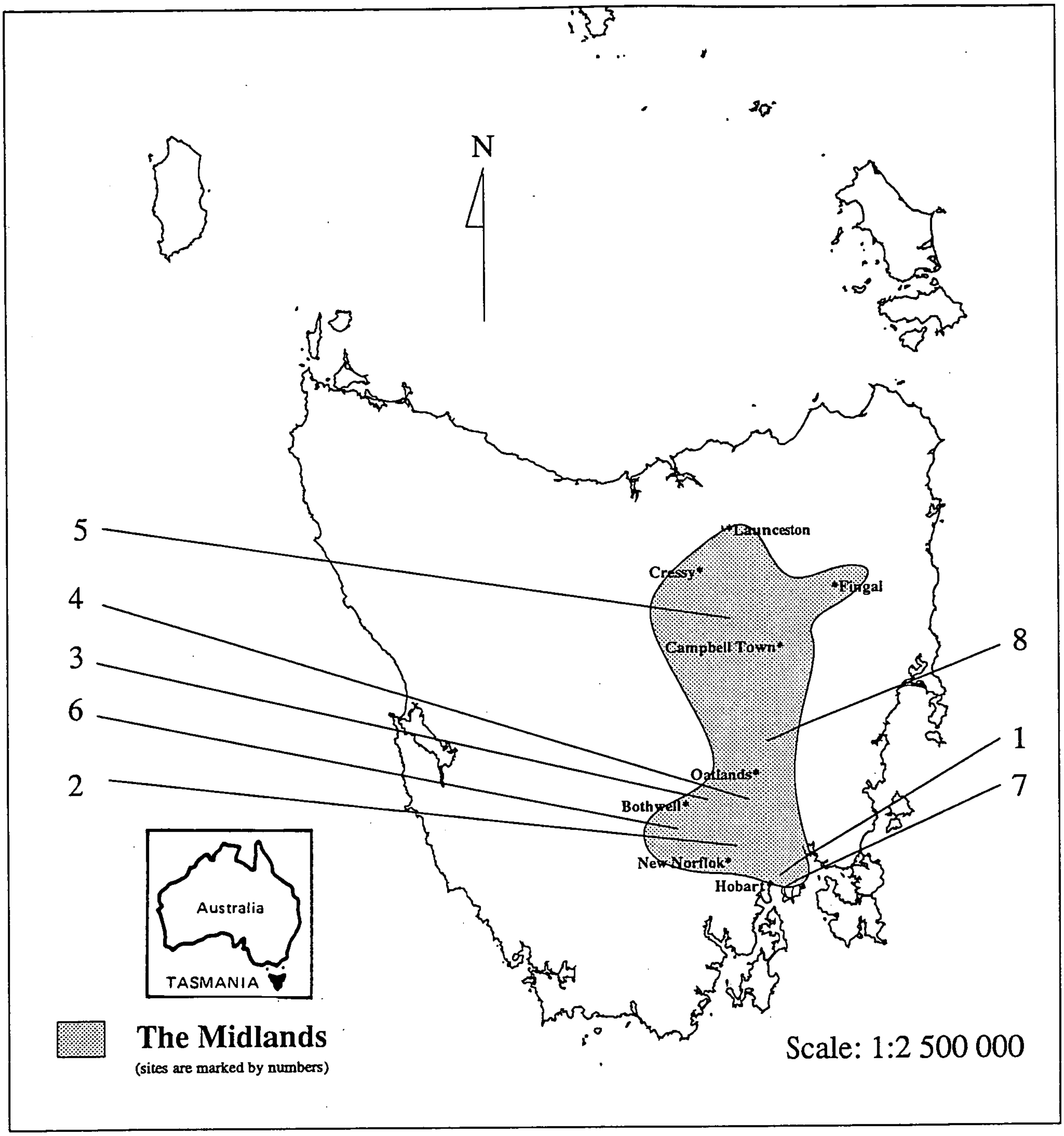

Figure A1.1. The Midlands of Tasmania.

Table A1.2. Study site descriptions. Numbers before site names corespond with numbers in Figure A1.1

Site	1. University Farm, Cambridge	2. Lovely Banks	3.The Square	4.Grove House	5.Fosterville	6.Wetheron	7. Richmond Golf Course	8. Wyndham
Altitude	20 m	280 m	440 m	400 m	180 m	400 m	80 m	360m
Aspect	SE	NE	N	SE	flat	SE	NE	NW
Gradient	14%	12%	10%	10%	flat	15%	5%	5%
Frost hazard	low	high	high	moderate	moderate	high	low	moderate
Precipitation	500-625 mm	500-625 mm	500-625 mm	500-625 mm	500-625 mm	500-625 mm	500-625 mm	500-625 mm
Exposure	Sheltered N and W; exposed S	Exposed W and SW	Exposed to N and W	Exposed to all weathers	protected from N and E	exposed to S and W	exposed to S and W	exposed to S and W
Drainage	good	good	moderate	good	good	good	good	good
Geology	Triassic sandstone	Triassic sandstone	Quaternary clays, silts and sands	Triassic sandstone	Triassic sandstone	Tertiary basalt	Triassic sandstone	Triassic sandstone
Soils	Fine sandy clay A horizon; medium clay B horizon	Sandy loam A horizon; Medium clay B horizon	Clay loam A horizon; deep clay B horizon	Uniform loamy clay	Duplex: sandy clay A horizon; medium clay B horizon	Uniform clay loam	Loamy sand A horizon; deep sand B horizon	Sandy loam A horizon; deep clay B horizon
Rural dieback	moderate	severe	moderate	moderate	severe	moderate	severe	low
Landuse	sheep grazing	sheep grazing	sheep grazing	Sheep grazing	Sheep grazing; fodder production	sheep grazing	bush conservation	sheep and cattle grazing
Remnant vegetation	EV; AV; BS; LL; *	EV';EP;AD;BS ;BM;LL	EP; LL	EP; AD	EV; EP; AD; LL; DS	EV; EP; AM; BS	EA; AD; CL; BM; LL; HR	EP; ET; AD; LL
Land systems classiification	Heathy Hills (zone S1) - 273141	Huntingdon Tier (zone I1) - 278141	Bothwell Flats (zone P) - 298225	Oatlands (zone S1) - 273231	Isis River Flats (zone P) - 298125	Brighton (Zone B1) - 282132	Heathy Hills (zone S1) - 273141	Oatlands (Zone S1) - 273231

* EV = *Eucalyptus viminalis*; AV = *Allocasuarina verticillata*; BS = *Bursaria spinosa*; LL = *Lomandra longifolia*; EP = *Eucalyptus pauciflora*; AD = *Acacia dealbata*; BM = *Banksia marginata*; DS = *Danthonia setacea*; AM = *Acacia mearnsiii*; EA = *Eucalyptus amygdalina*; HR = *Hibbertia riparia;* ET = *Eucalyptus tenuiramis*

Figure A1.2. An example of a typical revegetation site in the Midlands (Ouse).

APPENDIX 2. Seed Viability

Introduction

While germination or viability tests are in many ways artificial and may not reflect observations in the field, they give an indication of the ability of a seed to develop into a normal plant under ideal conditions (Anonymous 1966). There is, however, usually considerable discrepancy between the results of germination tests conducted under ideal laboratory conditions and the emergence of seedlings in the field (Roberts 1972). When viability tests are conducted, the rate, or speed, of germination can be measured as well as percentage germination, which can give an indication of the vigour of particular seedlots (McWilliam *et al.* 1970). Pollock and Roos (1972) consider the speed of germination to be an important aspect of vigour, although the rate of seedling growth is frequently used to evaluate this factor. A slow germination rate can leave seedlings susceptible to competition for space, nutrients, light and water, and attack by micro-organisms.

Seeds of some species will not germinate when exposed to favourable conditions without some form of pre-treatment, and are considered to be dormant. Dormancy can be classified as seed coat dormancy, which is broken by treatments which break the seed coat and allow water and gases to enter; or embryo dormancy, which is due to a metabollic block within the embryo, and can be broken by conditions which bring about physiological changes in the embryo, such as light, chilling or dry storage (Bonney 1987). Bonney (1987) notes that some eucalypts require pre-chilling or light to germinate. The requirements of many eucalypt species are now generally well known, and are described by Bonney (1987), Turnbull and Doran (1987) and Boland *et al.* (1980). A more limited list is given by the International Seed Testing Association (Anonymous 1985).

Different provenances of the same species can vary markedly in germination rate and percentage, and the strength and length of dormancy (Ladiges and Ashton 1974). Different provenances may exhibit different early vigour, which may influence establishment rates on particular sites.

In the following experiments, the seed viability and rates of germination of species used in previously described field and glasshouse trials was investigated.

Experiment 1. Species viability tests

Methods

In the field experiment at the University farm at Cambridge , the seed of a number of provenances of *Eucalyptus ovata, E. pauciflora* and *E. amygdalina* was mixed in equal proportions prior to sowing. Figure A2.1 gives the locations of these provenances. The viability of these pooled seedlots was tested in the following manner, using standard International Seed Testing Association procedures (Anonymous 1966).

Table A2.1. The seed provenances included in the sowing mixes for each species subjected to a viability test, and the sample weights used.

Species	Provenances*	Sample weight (g)
E. pauciflora	Avoca, Melton Mowbray, York Plains, Jericho	0.80
E. ovata	Avoca, Melton Mowbray, York Plains, Oatlands, Lower Marshes	0.10
E. amygdalina	Fingal, Royal George, Longford	0.40

* see Figure A2.1 for the location of these provenances

Two thicknesses of Whatman Number 9 filter paper were placed into each of 8 petri dishes. The paper was moistened using distilled water.

Weighed seed samples are generally used for germination tests with eucalypt species, because of the difficulty of separating the seed from chaff and undeveloped seed (Anonymous 1985). Four seed samples of *E. pauciflora* and *E. amygdalina* were randomly selected from the pooled seedlots, and weighed, using the weights recommended by Turnbull and Doran (1987) (Table A2.1), and then placed into 8 petri dishes, after which they were sprayed with a dilute solution of Benlate® to control fungal attack and refrigerated at 3°C for 3 and 4 weeks respectively. Each sample consisted of approximately 100 seeds. This was tested before accepting the recommended weights by counting the number of seeds in 3 weighed samples per species and averaging the number.

Unstratified samples of the 3 species were prepared in the manner outlined above, minus the refrigeration. Both stratified and unstratified seedlots were then placed in a constant 20°C environment until germination was complete. Germinated seeds were removed at each daily scoring. Rate and percentage germination were estimated. Rate was measured in terms of the number of days required for a given percentage germination to occur. Percentage germination was measured as the average total number of seeds germinated out of each sample. The number of viable seeds per kilogram was also determined, using the following Forestry Commission, Tasmania formula:

$$\text{N}^{\underline{\text{o}}}\text{. viable seeds kg}^{-1} = a \times 5000 \pm \sqrt{b} \times 965$$

where

a = mean number of germinants
b = sum of the squared difference of each seedlot from the mean

Results

Both rate (speed) and percentage germination varied between species and between stratified and unstratified seed (Table A2.2). *E. ovata* seed had a faster rate (less days) and greater percentage germination than unstratified *E. pauciflora* and stratified or unstratified *E. amygdalina* seed.

Cool moist stratification increased the rate of germination in both *E. pauciflora* and *E. amygdalina*. This was particularly evident with *E. pauciflora*, where the number of days to achieve 90% germination was reduced from 15 to 6.5 days following stratification.

Stratification also increased the percentage germination of the species tested. Percentage germination of *E. pauciflora* was increased by 39% after stratification, but *E. amygdalina* percentage germination was only increased by 2%, which was probably not significantly different from the unstratified.

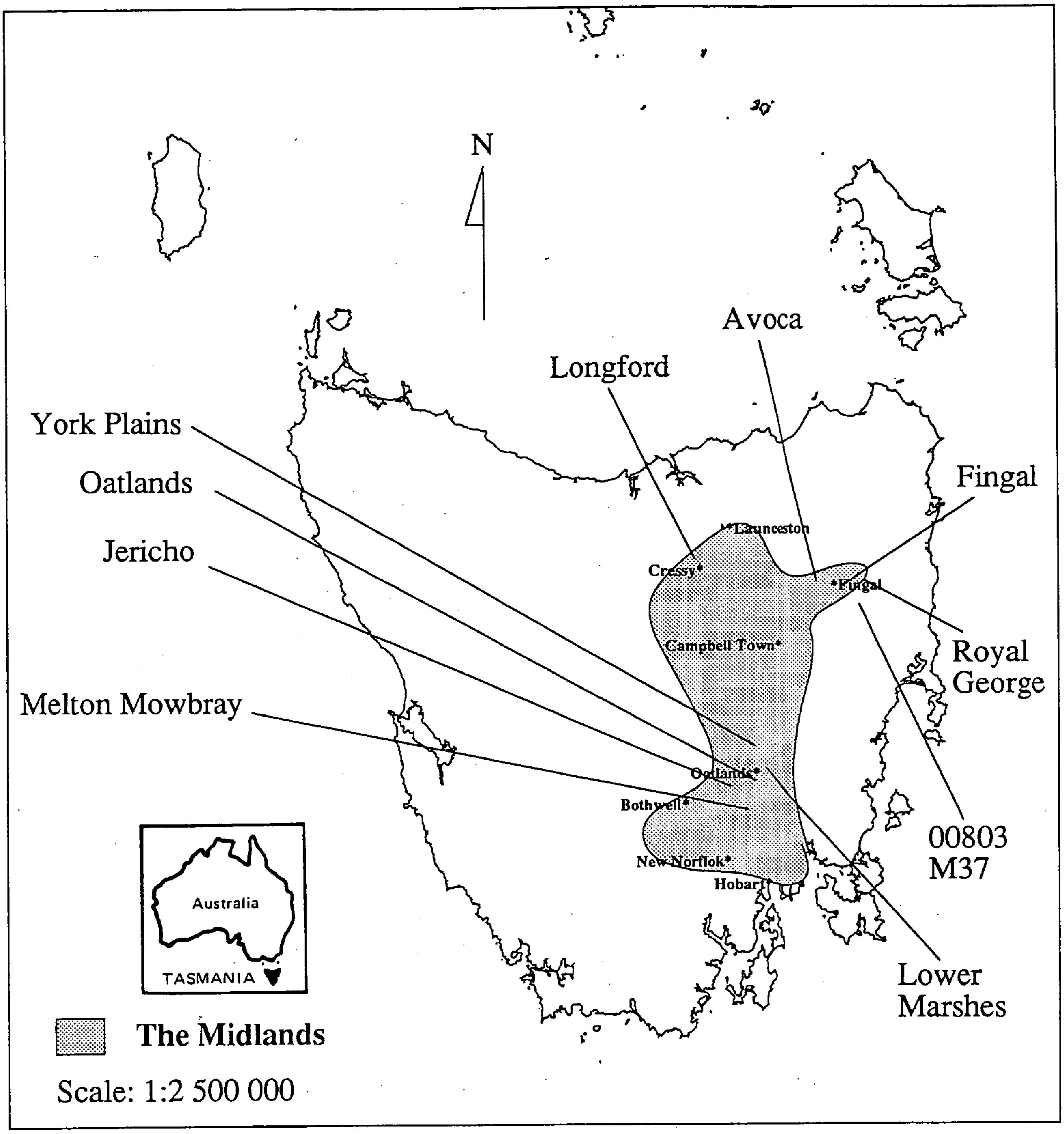

Figure A2.1. Location of seed provenances in the Midlands.

Table A2.2. Rate and percentage germination, and number of viable seeds per kilogram, for 3 eucalypt species. Different letters in columns indicate treatment differences.

Species	Nº. days 10% germination	Nº. days 50% germination	Nº. days 90% germination	Total % germination	No. viable seeds kg^{-1}
E. pauciflora (62 000)*	6.5^{a} (4.5-9.0)	9.5^{a} (8.0-10.5)	15.0^{a} (13.5-16.0)	29	145 000 (±4178)
E. pauciflora (stratified)	2.5^{b} (1.5-3.5)	3.5^{c} (3.0-4.0)	6.5^{c} (5.5-7.5)	48	240 000 (±13 440)
E. ovata (546 000)*	4.0^{ab} (2.5-6.0)	5.0^{bc} (4.0-6.0)	6.5^{c} (6.0-7.0)	97	483 500 (±14 280)
E. amygdalina (120 000)*	5.5^{ab} (4.5-6.5)	8.5^{a} (8.0-9.0)	11.0^{b} (10.5-11.5)	47	236 250 (±4 017)
E. amygdalina (stratified)	4.0^{ab} (3.5-4.5)	5.5^{b} (4.5-6.5)	9.0^{b} (8.0-10.5)	48	241 250 (±5 173)

* The numbers shown in brackets are the number of viable seeds per kg recorded by Turnbull and Doran (1987).

The number of viable seeds per kilogram measured in this experiment was higher than those reported by Turnbull and Doran (1987) and Boland *et al.* (1980) for *E. pauciflora* and *E. amygdalina*, but slightly lower than those reported for *E. ovata*.

Experiment 2. Provenance viability tests

Methods

The viability of the 3 provenances of *E. amygdalina* which made up the sowing mix used in the previous experiment was tested in this experiment. For comparison, a seedlot collected from the forest seed zone 00803 M37 (Forestry Commission, Tasmania Fingal area) was included, which was collected from the region bounded by the South Esk and St Paul rivers, and the east coast.

Viability tests were run in the manner outlined in the previous experiment. The seed was not stratified prior to sowing

Germination rate and percentage, and the number of viable seeds per kilogram were calculated in the manner outlined in Experiment 1.

Results

Both germination rate (speed) and percentage varied between provenances (Table A2.3). Germination rate was fastest in the Longford provenance and slowest in the Fingal provenance. Percentage germination was also lowest in the Fingal provenance. The highest percentage germination was recorded in the Royal George provenance. The rate and percentage germination of provenance 00803 M37 did not differ markedly from the other provenances.

Only the Fingal provenance had a lower number of viable seeds per kilogram than that measured by Turnbull and Doran (1987) and Boland *et al.* (1980).

Table A2.3. Rate and percentage germination, and number of seeds per kilogram, for 4 provenances of *E. amygdalina*. Different letters in columns indicate provenance differences.

Provenance	No. days 10% germination	No. days 50% germination	No. days 90% germination	Total % germination	No. viable seeds kg^{-1}
Longford	4.5^{c} (4.0-5.0)	7.0^{c} (6.5-8.5)	11.5^{c} (10.5-12.5)	67	337 500 (±20 490)
Royal George	6.0^{b} (5.5-6.5)	9.5^{b} (9.0-10.0)	16.0^{b} (14.5-17.5)	70	351 500 (±26 847)
Fingal	11.5^{a} (9.5-13.5)	15.5^{a} (14.0-16.0)	21.0^{a} (18.0-23.0)	20	103 750 (±7 074)
00803 M37	4.5^{c} (4.0-5.0)	9.5^{bc} (8.0-11.0)	14.5^{bc} (13.5-15.5)	34	171 250 (±12 865)
Turnbull and Doran*	-	-	-	-	120 000

* Number of viable seeds per kilogram measured by Turnbull and Doran (1987).

Discussion

An estimation of seed viability is important where direct seeding is used for plantation establishment, as it can be used to determine appropriate sowing rates (Anonymous 1986; Venning 1988). Where seed viability or percentage germination is low, it may be necessary to increase sowing rates to achieve a particular number of stems per hectare.

Roberts (1972) highlights the fact that the results of germination tests in the laboratory usually differ considerably from the emergence of seeds in a field situation. In addition, many factors other than seed viability affect the number of seedlings establishing on a particular site. However, the Victorian Department of Conservation, Forests and Lands (Anonymous 1986) and Venning (1988) both include a measure of seed viability in their formulae for estimating the quantity of seed required for direct seeding.

Germination rate can be used as a measure of vigour (Pollock and Roos 1972). It is possible that seed with a greater germination rate may have considerable advantages over those with a slower rate of germination, in terms of site occupation and competition for resources. Bonney (1987) suggests that a faster rate of seed germination may reflect a better seed quality, and goes on to note that delay in the full expression of germination is usually considered to be the earliest sign of quality loss in a seedlot. Although other factors also need to be considered, rate and percentage germination may be useful in choosing species provenances to be sown on a particular site.

The seed viability measured in the above experiment was generally higher than viabilities quoted for the same species by other authors. Both Turnbull and Doran (1987) and Boland *et al.* (1980) conducted a minimum of 10 tests on each species, whereas only 4 samples per seedlot were tested in the above experiments. It is possible that if more tests had been conducted, figures closer to those quoted by these authors may have resulted.

The above viability tests were used in the calculation of rate and percentage germination in the Cambridge field experiment and subsequent glasshouse work.

APPENDIX 3. Seed Harvesting

Introduction

Seed removal has been found in many instances to affect the results of direct seeding (Pryor and Clarke 1964; Cremer 1966; Majer 1990). Ants are often implicated in such activities (Majer 1990), although rodents (Buckley 1982) and beetles (Cremer 1966) have also been found to feed on seed. Russell *et al.* (1967) measured significant reductions in quantities of direct sown pasture seed as a result of ant removal. Pryor and Clarke (1964) and Purdie (1977) had similar problems with eucalypt seed in both pasture and forest locations. The following experiment was conducted to investigate rates of seed harvesting following direct sowing at one site in the Midlands.

Methods

The experiment was established on the University farm at Cambridge (see Appendix 1 for site details), in conjunction with a direct seeding trial. It was repeated twice, at monthly intervals, following direct seeding in September. Nine sites were randomly selected in the buffer strips surrounding each sowing plot, and marked with stakes. Three 'seed traps' (Figure A3.1) were placed at each site. These 'traps' were constructed from plastic takeaway food containers, of dimensions 12 x 4 cm, into which 2 'entrances' were cut at the junction of the wall and the floor (Andersen and Ashton 1985). Each entrance was 1 x 2 cm, and they were at an angle of approximately 33° from each other, to reduce wind funnelling.

Six lots of 15 seeds of the species *Eucalyptus pauciflora, E. amygdalina* and *E. ovata* were prepared for the first sowing, and nine of each for the second sowing. At each marked location, one seedlot of each species was placed into a separate 'trap' and marked with the species type. A rock was placed on each lid, to prevent the containers from blowing away. Species were randomly allocated to traps at each site.

Ten days from the time of seed placement, the traps were collected and the number of seeds remaining in each was recorded.

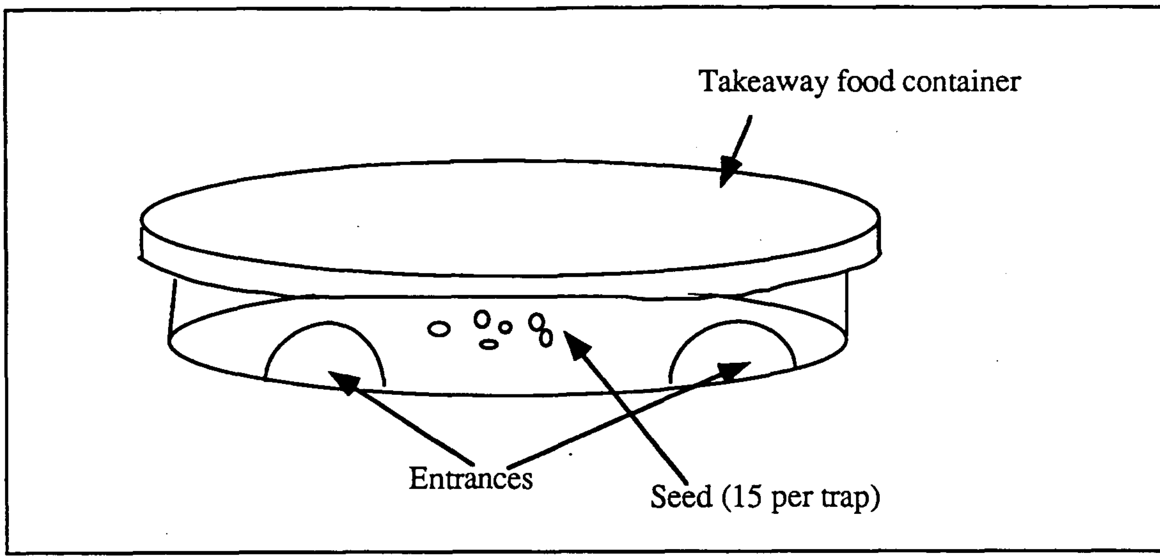

Figure A3.1. Seed traps used to monitor the harvesting of eucalypt seed

Results

The results from this experiment clearly demonstrate that there was removal of eucalypt seed from the Cambridge site (Table A3.1). The overall removal rate was much greater in October than in September. Seed removal varied between trap sites, ranging from 0 to 100%. There was also variability in the degree of removal of particular eucalypt species. In September, there was more browsing of *E. pauciflora* seed than of the other species, with *E. amygdalina* being the least-preferred species. In October, *E. ovata* was the most-browsed and *E. amygdalina* the least-browsed species.

At each trap site, the quantity of seed removed varied between September and October, although there was no consistent trend.

Table A3.1. Number of seeds removed from seed traps at the University farm at Cambridge.

Trap site	Percentage of seed removed from traps at two dates					
	12 September			12 October		
	E. pauciflora	*E. ovata*	*E. amygdalina*	*E. pauciflora*	*E. ovata*	*E. amygdalina*
1	0	0	0	40	53	0
2	20	13	0	0	66	40
3	0	0	0	100	100	100
4	46	73	0	0	86	40
5	86	0	20	0	93	0
6	33	0	0	86	20	0
7	-	-	-	20	93	0
8	-	-	-	66	53	33
9	-	-	-	53	0	56
Mean	30.8	14.3	3.3	36.5	56.4	29.9

Discussion

Although no attempt was made in this experiment to identify seed browsing species, it is assumed that ants were the major harvester. This is based on observations at other sites in the Midlands during earlier experiments. The seed trap design was such that most other browsing organisms would have been excluded.

Artificial seed baits are commonly used to investigate seed removal, although seed removal from traps is potentially very different from seed removal in nature (Andersen and Ashton 1985). Andersen and Ashton (1985) found that the use of petri dish seed traps, of a design similar to that described in the above experiment, had little effect on ant seed removal after 48 hours. They suggest that the results of seed bait experiments can be more accurately related to the field situation if the size of the seed clump chosen for the bait simulates natural seedfall. For example, if a species releases seed gradually, small clumps of 5 or less seeds should be used in seed traps, whereas larger clumps, of approximately 15 seeds, are more appropriate for species, such as eucalypts, which release seed *en masse*.

The degree of seed removal from traps may be intricately related to the type of harvester, and a lack of understanding of the species involved may lead to an over- or under-estimation of seed harvesting at a particular site (Andersen and Ashton 1985). It may also relate to the plant species. Seed harvesting is generally highly selective, and while the overall proportion of seed removal at a site may be relatively small, particular species may lose a large proportion of seed to predators (Buckley 1982). In the above experiment, less *E. amygdalina* seed was browsed than *E. pauciflora* or *E. ovata* seed, which may explain to some extent the greater germination percent recorded for that species in the field experiment outlined in Chapter 3. In October, the proportion of *E. ovata* seed harvested was much greater than that of the other species, which may reflect the smaller seed size, or could be related to the type of harvester. In September, there appeared to be a preference for *E. pauciflora* seed.

The rate of seed removal from traps may also be related to variable density of harvesters. Andersen (1983) suggests that, where ants are the main seed harvesters, such variability is related to the colonial habit of ant populations. This may distort the results of seed harvesting studies.

Ashton (1979) found that seed of *Eucalyptus regnans* disappeared within three weeks of exposure to harvesting ants. Andersen and Ashton (1985) consider that most removal occurs within 10 days, covering a range of weather conditions. During dry summer conditions or cold periods, a large proportion of seed may therefore be removed before there is an opportunity for germination to occur.

Seed harvesting activity by ants is generally considered to vary seasonally. Andersen (1983) found that ant activity was highest in summer and lowest in winter, with pronounced seasonal differences in ant species composition. Johns and Greenup (1976) found that harvesting of pasture seed fell to less than 1% of total seed during winter, but was as high as 90% in summer. Buckley (1982) suggests that ant foraging activities are strongly influenced by physical environmental conditions such as light, temperature and humidity. The differences measured between months in the above experiment may be related in part to seasonality.

The results of this experiment suggest that seed harvesting could potentially have a significant effect on the outcome of direct seeding in the Midlands. To minimize such problems, a knowledge of browsing patterns would be very useful, and remedial action may be necessary. Many authors have investigated seed treatments to reduce predation by insects. Pryor and Clarke (1964) treated soil with dieldrin prior to sowing with flooded gum seed, and measured significantly greater germination than in untreated soil. Cremer (1966) found that spraying the ground with dieldrin as much as trebled the germination of *E. regnans*. He also experimented with pelleting seeds with insecticides, which improved the percentage germination. Russell *et al.* (1967) found that pelleting pasture seed with insecticides stopped seed removal by all classes of ants. However, 9 of 14 pesticides tested by Neuman and Kassaby (1986) were found to be moderately or severely phytotoxic when applied to seed testas, resulting in reduced germination of eucalypt seed. Purdie (1977) found that application of malathion or chlordane to eucalypt seed was insufficient to prevent predation by insects.

To avoid using chemicals, Majer (1990) suggests either drilling the seed or sowing it with mulch material, both of which may protect the seed from browsing by making it more difficult to find. Percent germination of some species may, however, be reduced when sown at depth (Cremer 1966). Andersen and Ashton (1985) found that the presence of litter material greatly reduced removal rates of *E. baxteri* seed, although they did not investigate the effect of such material on germination of this species.

Ashton (1979) discusses the role of fire in reducing the population of seed-harvesting organisms. Majer (1990) suggests that the most effective way of reducing seed browsing problems may be to sow seed at a time when the activity of browsing organisms is low. Alternatively, if it is known that harvesting organisms exist at a given site, the sowing rate could be increased to simulate massive seedfall, resulting in temporary saturation of harvester populations, thereby increasing the probability of some seeds entering safe germination sites (Ashton 1979; Andersen and Yen 1985). This in many instances would not be economically feasible.

While the results of the experiment described above suggest that seed harvesting did occur at the Cambridge site, nothing is known of the species involved in harvesting, or the extent of harvesting activities in the Midlands. Further research is required to understand the significance of seed harvesting activities on the establishment by direct seeding of woody vegetation in the Midlands.

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